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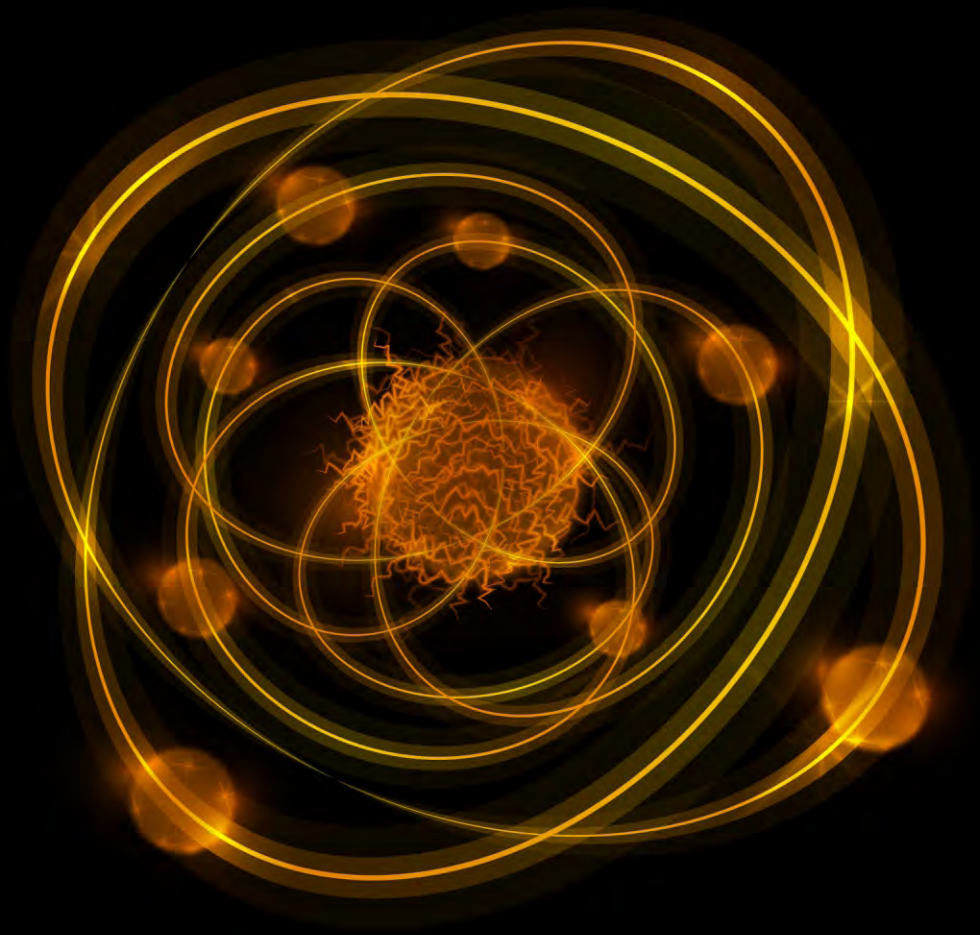

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Lead-Bismuth and Lead as Coolants for Fast Reactors

G. I. Toshinsky[1,2*], A. V. Dedul[1], O. G. Komlev[1], A. V. Kondaurov[1], V. V. Petrochenko[1]

[1]JSC "AKME-Engineering", Moscow, Russia
[2]JSC "SSC RF-IPPE", Obninsk, Kaluga, Russia
Email: *toshinsky@ippe.ru

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Abstract

Fast reactors used lead-bismuth eutectic (LBE) and lead as coolants possess very high level of inherent self-protection and passive safety against severe accident. So, population radiophobia can be overcome. That type of reactors can be simultaneously more safely and more cheaply. As all other coolants, LBE and lead coolant (LC) possess the certain virtues and shortcomings. The presented report includes the comparative analysis of characteristic properties of those coolants, their impact on reactor safety, reliability and operating characteristics. The conclusion is made about promising usage of FRs with these coolants in future NP after the experience in operating of the prototypes of such reactors has been obtained.

Keywords

SVBR-100, Fast Reactor, Lead-Bismuth Coolant, Lead Coolant, Nuclear Power Plant, Inherent Self-Protection, Melting Point, ^{210}Po, Bismuth Recourses

1. Introduction

To provide sustainable development of the future nuclear power (NP), it must be large-scale one. It is possible for use of fast reactors (FR), which breeding ratio (BR) is equal or exceeds one, operating in the closed nuclear fuel cycle (NFC). That makes it possible to involve ^{238}U (widespread heavy uranium isotope) instead of ^{235}U (rare light uranium isotope) in generation of electric power at the NPP. Due to the highlighted fact, the source of raw fuel for the NP can be extended approximately one hundred times more thus providing the people with energy for many thousands of years without carbon release into the atmosphere and consumption of oxygen. To realize that opportunity, the FRs must operate

in the closed NFC with recycling of built-up plutonium. At the same time, the future large-scale NP must be competitive with fossil power plants (FPPs) and must deterministically eliminate the severe accidents requiring population evacuation. At present, in the world there are no nuclear power technologies (NPTs), which can meet all the highlighted requirements. However, now such NPTs are developed in many countries.

Along with that, to this day the FRs are not developed widely. Moreover, at present the time for their economically expedient implementation in the NP is being postponed. For instance, in the USA, where the park of thermal reactors (TR) is the largest (about 100 GWe), it is not planned to implement FRs in the current century due to considerable increase of the natural uranium cost that can result in loss in competitiveness of the NPPs based on TRs with FPPs.

The main reason is that FRs are much more expensive than TRs. That is conditioned by the fact that everywhere the sodium was selected as coolant as possessing the best heat-transfer properties, which allowed providing of intensive heat removal in the core and high rate of excess plutonium buildup (short plutonium doubling time). The highlighted requirement to FRs was a determining factor in the last seventies due to existing conditions, when the resources of cheap natural uranium were explored in low scales and the pace of electric power development and especially NP development was high. The required doubling time of plutonium (and consequently the time of doubling of the number of NPP power units) was ten years and less.

The lower economical parameters of those FRs associated with additional expenditures for safety caused by natural properties of sodium, namely: extremely high chemical activity while contacting with water and air that is possible in accidental situations. Those additional expenditures are caused by the necessity to provide the following: 1) intermediate sodium circuit between the radioactive sodium primary circuit and steam-water circuit, 2) casing of sodium pipelines, 3) more complicated technology of SNF handling prior to installation of the unloaded fuel sub-assemblies (FSA) in the cooling water pool, 4) special measures on fire-prevention and hydrogen safety. In the result, the future large-scale NP is necessarily planned as a dual-component one, namely: in the closed NFC the more expensive sodium fast reactors (SFR) "are feeding" the cheaper TRs by their excess plutonium.

At present in most countries, where development of NP is realized, there are no external factors highlighted above. For that reason, use of sodium in FRs is not without alternatives. Use of heavy liquid metal coolants (HLMCs) as FR coolants, which heat-transfer properties are much worse as compared with those of sodium, does not allow obtaining of short plutonium doubling time. However, due to the natural properties of chemical inertness and extremely high boiling point, it forms the backgrounds for construction of FRs with a very high level of inherent self-protection that deterministically eliminates severe accidents requiring the population evacuation (the more detailed the consideration of that question was given in Paper (Ref. [1]) for LBE cooled FR). At this point, the FRs are

not burdened with additional expenditures for safety required for both, water cooled TRs and sodium cooled FRs. Due to that fact, after demonstration of that technology it is possible to consider one-component structure of the future large-scale NP based on FRs with HLMCs as an option. More detail use HLMC in FRs is considered in Paper (Ref. [2]).

In this case the conflict between the increasing safety requirements, unavoidable in the future, and economics requirements can be eliminated. The highlighted conflict that is peculiar to reactor facilities (RF), which use coolants with large amounts of accumulated potential energy (compression energy, chemical energy), is as follows: rise in safety requirements due to expected significant increase of NPP power-units in future is inevitably resulting in growth of the number of safety systems and their power capacity, increase of the number of defense barriers. Thus, the capital and operating costs are growing and the NPP competitiveness is lowering. For comparison, in water coolant, sodium coolant and heavy liquid metal coolants the values of accumulated potential energy (compression and chemical energy) are 20, 10 and zero GJ/m^3 correspondingly (Ref. [3]). Use of HLMC is forming the backgrounds for simplification of the RF design due to elimination of the certain safety systems required in the RFs with other coolants. Thus, it is possible to construct NPPs on the basis of FRs with HLMC, which aren't only safer, but cheaper, as compared with NPPs based on traditional type reactors.

The Global Agreement on Climate, that was accepted by 196 parties on 12. 12. 2015 and signed on 22. 04. 2016 at UN Climate Change Conference held in Paris and purposed to replace the Kyoto Protocol, will come into force in 2021 and does not specify the concrete ways of lowering of carbon exhausts into the atmosphere. It does not provide establishment of the mandatory tax on carbon exhaust as well. Moreover, the nuclear option is not provided in the Agreement, and that is conditioned mainly by radiophobia of the population, whose opinion is accounted by politicians. Along with that, large-scale development of the NP provides the opportunity of considerable lowering of carbon released into the atmosphere.

Those are the reasons, which provide the necessity for future changeover to the reactors with the considerably higher level of inherent self-protection. In such reactors the severe accidents requiring the population evacuation must be deterministically eliminated, *i.e.* the reasons to cause severe accidents will be excluded. RFs with HLMC will make it possible to overcome the population radiophobia that has grown again after the accident occurred at NPP Fukushima 1. It is much easier to convince the population in the NPP safety if it is provided by nature laws (e.g. absence of pressure in the reactor, lack of hydrogen release assure that explosion cannot occur and so on), which eliminate the internal reasons for those consequences. It is more clearly understood for the people, who consider the events on the basis of their own experience, but not on the results of probabilistic safety analyses.

2. Natural Properties of Lead-Bismuth and Lead Coolants and Their Impact on Fast Reactor Characteristics

2.1. LBE and LC Common Properties

1) ***Extremely high boiling point***, namely: 1670˚C and 1740˚C correspondingly for LBE and LC. Thus, the necessity to provide high pressure in the primary circuit and heat-removal crisis are eliminated. That eliminates also the opportunity of HLMC loss (LOCA) with core melting. Besides, that exclude high pressure radioactivity release and allow designing the protective shall only against of external impact (aircraft fall);

2) ***Chemical inertness*** while contacting with air and water. So, there are not reasons for forming of hydrogen in all accidental situations, reactor explosion and fires. HLMC chemical inertness regarding to water is eliminating the necessity in the intermediate circuit. To localize the events with leak in SG tubes, the steam condensers are provided in the primary circuit gas system. In an event of their failure it is provided that steam-gas mixture is passively discharged to the bubbler via the rupture membranes (bursting disk). The hydraulic diagram of HLMC circulation in the reactor is realizing effective gravitational separation of steam bubbles on the HLMC free level under the reactor lid. Experience of operating the LBE cooled reactors at nuclear submarines (NS) has revealed that in an event of small leak in the SG (up to 10 kg/h) there is no necessity in immediate RF shutdown (Ref. [4]);

3) ***Coolant compatibility with oxide fuel*** is eliminating the event that the accidental situation with untightness in the fuel element cladding is developing in the event with direct contact fuel and coolant with release of radioactivity in coolant how it happens quickly in PWRs and SFRs.

(These three properties assure a very high level of inherent self-protection allowing elimination of the certain safety systems and cheapening of the NPP);

4) ***Very low moderation of neutrons*** on lead and bismuth nuclei as compared with FRs cooled by other coolants. That results in heightening of efficiency of nuclear transmutation of minor actinides (MA), which possess the threshold dependence of microscopic fission cross-sections on neutron energy. As a result, while FRs are operating in the closed NFC, in a certain time the concentration of MA nuclei (neptunium, americium, curium) upon their recycling is reaching saturation as the rate of their loss caused by fission becomes equal to the rate of their formation. At that point, the specific radioactivity of MA (counting on one GW-y of produced power) will decrease with increase of cumulative energy-generating (Ref. [5]). So, it makes easier finding the solution to the problem of MA management at the back-end stage of the NFC, including the accelerated driven system (ADS), because long-lived isotopes of MA determine the radiotoxicity of the waste, which should be sent to the final burial. The harder neutron spectrum is also leading to diminishing of the positive constituent of void reactivity effect by making it negative for small power FRs with high neutron leakage. And this is important for safety;

5) ***To provide corrosion resistance*** of steels, in both coolants it is required to maintain the concentration of dissolved in coolant oxygen within the specified limits for the purpose to provide thermo-dynamical stability of protective oxide cover on the steel surface, and use of relevant devices for maintenance of coolant quality. Today these problems resolved successfully (Ref. [6]);

6) ***High density of HLMC*** that requires to reduce the flow velocity for the purpose to prevent high consumption of energy for coolant circulation, use of special seismic insulation against the earthquake, especially for large unit capacity reactors, and tacking into account buoyancy steel and fuel sub-assemblies in the coolant;

7) ***Comparatively low thermal conductivity of HLMC*** that restricts the opportunity to achieve high heat flux from the surface of fuel element claddings.

The last two properties exclude obtaining of high core power density and short plutonium doubling time as in the FR with sodium coolant.

2.2. Differing Properties and Characteristics of LBE and LC

2.2.1. Melting Point

The melting point of LBE is much lower (124˚C) as compared with that of LC (327˚C). It results in the following distinctions in RF characteristics:

- Considerable widening of the operating temperature range for LBE as compared with that for LC. It means that at the core outlet the temperature of both coolants must be limited by the same value (500˚C - 550˚C) determined by corrosion resistance of steels, the coolant temperature at the core inlet for LC must be considerably higher than that for LBE. It is necessary for the purpose to eliminate LC solidifying in normal operation mode, in transient modes, modes of start-up and shut-down cooling. Under the same power, reduction of LC heating in the core can be only achieved due to heightening of flow rate. Under corresponding increase of LC velocity, it will lead to increase in pump capacity as cubic dependence on flow rate. Provided the LC velocity is maintained as that of LBE, it results in increase of the core flow cross section that can be obtained by growth of its diameter or by diminishing of volume fraction of fuel. In both cases, under use of LC the RF technical and economical characteristics will be deteriorated;
- To eliminate LC "freezing" in the steam generator (SG), the higher temperature of its melting requires heightening of the temperature of feeding water supplied in the SG that results in the necessity to rise the steam pressure and, correspondingly, boiling temperature of water, as well as to inclusion in the secondary circuit hydraulic diagram the additional heater for feeding water heating to the temperature exceeding the melting point of lead (327˚C). That raises the RF cost, complicates it, increases the power consumption for own needs under slight increase of thermo-dynamical cycle efficiency;
- The necessity to maintain the LC temperature at a level close to 400˚C eliminates performance of repair works, replacement of the equipment and RF servicing without use of the robotized equipment.

2.2.2. Volume Change while LBE and LC Melting

Experience of operating the LBE cooled RFs at nuclear submarines has revealed that unintended "freezing" of coolant in the RF cannot be excluded. For the purpose to maintain the equipment operability, it results in the necessity of safe heating and "unfreezing" of coolant in the RF (Ref. [7]).

In accordance with reference (Ref. [6]), the LBE volume does not change in the process of melting. After LBE "unfreezing", this fact provided the operable state of the equipment in the LBE cooled RF including the operability of the whole primary circuit in the RF of first experimental NS K-27 of Project 645 after several years of "frozen" state. It was also favored by comparatively low range of temperatures from 20˚C to LBE melting point of 123.5˚C while RF heating when mechanical stresses in the equipment arise because of difference in thermal expansion factors of LBE and steel, that is, stresses in the structures did not lead to their deformation. One more property of LBE should be highlighted, namely: slow spontaneous increasing of LBE volume in the solid stage that is approximately 0.5% for two months and is conditioned by changes in crystal structure (Ref. [7]). In specially performed experiments the slow "self-extrusion" of LBE through the small hole was observed. However, low hardness and high plasticity of the solid LBE excluded development of damages in the equipment.

The possibility of safe "freezing-unfreezing" of LBE while maintaining the operability of the equipment is also important to ensure the transportation of modular small-power RF with loaded fuel and solid LBE (nuclear "battery") and long-term storage of SNF (Ref. [8]).

At the same time, when melting, the lead volume is increased by 3.7% (Ref. [6]). The range of temperature change in the process of heating from 20˚C to LC melting temperature of 327˚C is much higher than that for LBE. These factors should be accounted in the course of mastering the LC "unfreezing" mode, bearing in mind that shrinkage holes forming in the process of lead solidifying will be formed in some points of the primary circuit, and volume increase in the process of melting will occur in other points of the circuit.

2.2.3. Generating of Alpha-Active Radionuclide ^{210}Po

In LBE this parameter is much worse than that in LC. Rate of ^{210}Po generating in LBE is 10^4 times more than that in LC.

In normal operating conditions the LBE polonium activity is not shown, though it is a source of potential radiation hazard that must be accounted while developing and operating the NPP based on LBE cooled RFs. Radiological hazard of ^{210}Po is revealed when LBE or gas contacting with LBE is penetrated in servicing rooms. Such events occurred in accidents and repairs of the NS reactor facility and ground-based facilities-prototypes in the period of their mastering.

As operating experience of the NS RF has revealed, after reducing of temperature and solidifying of the spilled LBE, release of ^{210}Po aerosols and air radioactivity decrease sharply in accordance with thermodynamics laws. Fast solidifying of spilled LBE restricts the area of radioactive contamination and makes possible removal of the spilled LBE in a form of solid radioactive waste.

In an event of accidental loss of tightness in the primary circuit, low concentration of polonium in LBE (10^{-6} mol) and formation of thermodynamically stable chemical compound of polonium with lead set conditions for low concentration of ^{210}Po in air.

To perform repair and maintenance works on the contaminated equipment, works on removal of spilled coolant (approximately 20 tons at 27/VT Facility), the measures on individual and collective protection of the personnel (such as respirators, protecting clothes, organization of ventilation) were developed. Moreover, the following methods were developed: methods of decontamination of the equipment, fixing of activity on surfaces, techniques of performance of repair and maintenance works, which reduced the risk of penetration of ^{210}Po in hazardous amounts into the human organism and on the skin.

The personnel, who took part in those works, was subjected to periodic examinations, and based on multiple radiometric analysis of biological tests of the personnel (both military and civilians), the absence of events with presence of incorporated polonium in human organisms over the permissible levels was established (Ref. [9]). That fact validated a high efficiency of used individual and collective protection measures, the right option for the technology and correct organization of repair and maintenance works. It was also promoted by comparatively quick polonium washout from the human organism resulted from metabolic processes (effective period of semi-ejection was approximately 30 days) and very low molar concentration of polonium in LBE that lessened its volatility as compared with pure polonium. All the more, it is right for the integral design RF with protective casing that eliminates the opportunity of LBE leaks.

In Paper (Ref. [10]) published in the USA the data on retrospective analysis of mortality among the personnel who were dealt with released ^{210}Po on Mound Facility in 1944-1972. They were examined for ^{210}Po internal irradiation. Medical protocols of bioassays (over 160,000 bioprobes) were analyzed for the group of 4402 white men dealt with ^{210}Po during that period (104,326 man·years) and these data were compared with the official data on death reasons for 987 men from this group during the period till January of 1984.

The statistical data on mortality among this group was also compared with the corresponding data for two reference groups (average over the USA and over Ohio State). The conclusion was made that there was no correlation between polonium internal irradiation doses up to 1 Sv (100 rem) and mortality level caused by malignant formations. Practically, all observed trends, which characterized death-rate caused by cancer in the studied group, were negative, *i.e.* mortality in the examined group was even less than in two monitored groups.

On carrying out the investigations and examining the obtained experience, the American and Japanese experts have come to conclusion that formation of polonium in LBE cannot impede LBE use in future NP (Ref. [11], [12]). This is verified by the fact that works on development of LBE cooled fast reactors are realized in certain countries (namely: SVBR-100 in Russia, MYRRHA in Belgium, CLEAR in Chinese People's Republic, etc.).

It does not consider the use of LBE in ADS when, as a result of nuclear spallation reactions as a result of direct interaction of high-energy protons and neutrons with lead and bismuth nuclei, a significantly larger number of different polonium isotopes and more dangerous radionuclides (^{206}Hg) are formed. At high energies of protons and neutrons as in the ADS, the difference between cross-section of lead and bismuth is insignificant.

2.2.4. Lead and Bismuth Resources, Production Scales and Costs

Resources, scale of production and cost characteristics for LC are better than those for LBE. Lead is widespread in more amounts in nature, its explored resources and production scales do not limit LC use in NP, the cost of lead is lower than that of bismuth.

Up to present, the available data on explored bismuth resources has not allowed LBE application in the large-scale NP. However, not long ago the specialized Rosatom enterprises, namely: JSC "Atompedmetzoloto" and VNIPI promtehnologii have realized technical and economical investigations into the opportunity to organize large-capacity bismuth production in Russia and assessment of bismuth resources in the Commonwealth of Independent States (CIS). Their results have revealed that in Russia on the basis of explored bismuth deposits in the only Chita region, it is possible to realize profit-making production of bismuth in quantities, which are sufficient enough to put in operation approximately 50 GWe of NPPs with LBE cooled FRs with a pace of 1 GWe per year (Ref. [13]). Moreover, there are large bismuth resources in the North Caucasus. It is possible to put in operation ~250 GWe using the bismuth mines of Kazakhstan. The assessments made by Japanese experts have shown that available bismuth resources are approximately 5 million tons (Ref. [12]).

It should be highlighted that in compliance with general geological and economical laws, the quantity of mineral resources increases proportionally to the squared cost that the consumer is ready to pay for those resources.

For the current world's costs of bismuth, its contribution to the capital costs for construction of the NPP based on FRs does not exceed several percent shares. For that reason, the technical and economical parameters of the NPP will not be noticeably worth even when the bismuth cost increases several times. In addition, lead and bismuth can be used to produce LBE without deep purification of lead from bismuth and bismuth from lead, which reduces the cost of LBE. After decommissioning of the RF, LBE can be used repeatedly many times in the new RFs by refining, if it is necessary. In the future when the cheap bismuth resources have been expired, it will be possible to change over to lead-bismuth alloy of a non-eutectic composition with reduced bismuth content and higher boiling point. For example, when bismuth content in the alloy is reduced to 10% (5.5 times), the melting point is increasing from 123.5˚C to 250˚C that is considerably lower than the melting point of pure lead (~327˚C) and does not make excessive difficulties for RF operation.

2.2.5. Degree of LBE and LC Mastering

As for this parameter that is sometimes named technological readiness level (TRL), the LBE much outshines the LC as there is many-year experience of operating the LBE cooled reactors at Russian NSs and ground-based facilities-prototypes, which operation in all modes is approximately 80 reactor-years. Development of RFs with LBC was realized in conditions of absence of necessary knowledge and experience. Moreover, the fixed directive terms of work completion practically eliminated the opportunity for performance of related scientific and research works that caused a number of failures at the stage of mastering of that technology.

Of course, this operating experience, which at the initial mastering stage was followed by different accidents caused by absence of necessary knowledge and experience (Ref. [4]), cannot be impressive enough for the civilian RFs.

Along with that, in the part of RF maintenance, equipment repair and replacement, SNF refueling and storage, modes of coolant technology, providing of radiation safety while operating with the polonium contaminated equipment, LBE "unfreezing" modes, the obtained experience is sufficiently representative.

For that reason, construction of LBE cooled RFs is associated with noticeably less technical and financial risks in compare with lead cooled FRs.

3. Conclusions

1) In the RFs with LBE and LC the amount of accumulated potential energy in coolants is minimal that makes possible realization of inherent self-protection and passive safety properties to a maximal extent and elimination of the reasons of severe accidents requiring the population evacuation. Such properties of RFs with LBE and LC will make it possible to overcome the population radiophobia that has grown again after the accident occurred at NPP Fukushima 1. That is very important for large-scale and sustainable development of NP. As the third Director General of the IAEA Hans Blix said, "If the accident occurs somewhere, it is an accident everywhere." Therefore, chain of safety of large-scale future NP shouldn't have weak links.

2) As all other coolants, LBE and LC possess advantages and drawbacks considered in Section 2. Their impacts on NPP technical and economical characteristics, safety and reliability are different. The main common properties of LBE and LC are very high boiling point and chemical inertness while contacting with air and water. It is these properties assure a very high level of inherent self-protection allowing elimination of the certain safety systems and cheapening of the NPP. The main different property of these coolants is higher melting point of lead, which will make operation lead cooled FRs more difficult.

3) It is not possible to give preference to any coolant without construction and obtaining of real operating experience for experimental (demonstrational) prototypes of NPP RFs with lead-bismuth and lead coolants. Along with that, for LBE cooled RF the technical and financial risks, which follow mastering of each innovative technology, will be much less due to having experience of LBE cooled reactors, than those for RF with lead coolant that has no experience of application in the reactors.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviation

ADS: Accelerated Driven System
BR: Breeding Ratio
CIS: Commonwealth of Independent States
FPP: Fossil Power Plant
FR: Fast Reactor
FSA: Fuel Sub-Assembly
HLMC: Heavy Liquid Metal Coolant
IAEA: International Atomic Energy Agency
LBE: Lead-Bismuth Eutectic
LC: Lead Coolant
LCOE: Levelized Cost of Energy
MA: Minor Actinides
NFC: Nuclear Fuel Cycle
NP: Nuclear Power
NPP: Nuclear Power Plant
NPT: Nuclear Power Technology
NS: Nuclear Submarine
PSA: Probabilistic Analysis Method
RF: Reactor Facility
SFR: Sodium Fast Reactor
SG: Steam Generator
SNF: Spent Nuclear Fuel
SVBR: Lead-Bismuth Cooled Fast Reactor
TR: Thermal Reactor
TRL: Technological Readiness Level

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Ground States Structure of Ruthenium Isotopes with Neutron $N = 60, 62$

I. Hossain[1*], Huda H. Kassim[2], Mushtaq A. Al-Jubbori[3], Fadhil I. Sharrad[2,4], Said A. Mansour[1]

[1]Department of Physics, Rabigh College of Science & Arts, King Abdulaziz University, Jeddah, Saudi Arabia
[2]Department of Physics, College of Science, Kerbala University, Karbala, Iraq
[3]Department of Physics, College of Education for Pure Science, University of Mosul, Mosul, Iraq
[4]College of Health and Medical Technology, Al-Ayen University, Al Nasiriya, Thi Qar, Iraq
Email: *mihossain@kau.edu.sa

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Abstract

In this paper, Ruthenium Isotopes with neutron $N = 60, 62$ have been studied the ground state bands using Matlab computer code interacting boson model (IBM-1). We apply IBM-1 formula for O(6) symmetry in Ru isotopes with neutron $N = 60, 62$. The theoretical energy levels up to spin-parity 12^+ have been obtained for ^{104,106}Ru isotopes. The yrast states, gamma band, beta band, and B(E2) values are calculated for those nuclei. The experimental and calculated $R_{4/2}$ values indicate that the even-even $^{104\text{-}106}$Ru isotopes have O(6) dynamic symmetry. The calculated results are compared to the experimental data and are found in good harmony with each other. The plots of the potential energy surface of both nuclei are O(6) characters.

Keywords

Ruthenium Isotopes, Interacting Boson Model-1, Potential Energy, Energy Level

1. Introduction

Recently, Ruthenium isotope has been a focus of the nuclear structure of many theoretical and experimental investigations. The low-lying even nuclei had been successfully explained nuclear collective characters using the interacting boson model-1 (IBM-1) [1]. In the first beginning the collective states can be described by a system of identical bosons N_B. These are S-boson $L = 0$ and d-boson $L = 2$. There is no discrepancy between neutron and proton in IBM-1. There are three dynamical symmetries indicated by U(5), SU(3) and O(6) analogous to spherical vibrator, deformed rotor, and γ-soft respectively. The microscopic a harmonic

vibrator approach (MAVA) used in investigating the lower level collective states in Ruthenium isotopes [2].

The Ruthenium isotopes have atomic number $Z = 44$. It belongs near to closed shell Sn (magic number $Z = 50$). The external forms of even $^{104\text{-}106}$Ru isotopes have $g_{9/2}^{-6}$ (6 proton holes) and $g_{9/2}^{10,12}$ (10 and 12 neutron particles) close to magic number 50. This configuration has been investigated the ground state structure from spherical to deformed symmetry. The edifice of yrast levels and electromagnetic strength of Ru isotopes studied by many scientists [3] [4] [5] [6] [7].

Recently, the properties of the yrast level were studied in Pd isotopes with even neutron $N = 54$ - 64 [8]. The electromagnetic reduced transition strength of Cd isotopes with $N = 66$ - 74 were investigated [9]. The B(E2) value of yrast band of even $^{102\text{-}112}$Pd and $^{96\text{-}102}$Ru isotopes [10] [11] [12] were investigated by interacting boson model (IBM-1). The low-lying level of ^{184}W and ^{184}Os nuclei were investigated [13] [14].

The present aim particularly focuses on the structure of the ground state band and the potential energy surfaces to find the dynamical symmetry of even $^{104\text{-}106}$Ru isotopes by the application of IBM.

2. Method of Calculation

The Interacting Boson Model (IBM) gives occupation to truncated model space for nuclei with N number of nucleons. It provides a quantitative description of identical particles with forming pairs of angular momentum 0 and 2.

The Hamiltonian of IBM-1 [15]:

$$H = \sum_{i=1}^{N} \varepsilon_i + \sum_{i<j}^{N} V_{ij} \tag{1}$$

Here ε is energy of boson and V_{ij} is the potential energy of boson between i and j.

Hamiltonian is from multi-pole form [16]

$$H = \varepsilon \hat{n}_d + a_0\left(\hat{P}\cdot\hat{P}\right) + a_1\left(\hat{L}\cdot\hat{L}\right) + a_2\left(\hat{Q}\cdot\hat{Q}\right) + a_3\left(\hat{T}_3\cdot\hat{T}_3\right) + a_4\left(\hat{T}_4\cdot\hat{T}_4\right) \tag{2}$$

Here

$$\hat{n}_d = \left(d^{\dagger}\cdot\tilde{d}\right),\quad \hat{P} = \frac{1}{2}\left(\tilde{d}\cdot\tilde{d}\right) - \frac{1}{2}\left(\tilde{s}\cdot\tilde{s}\right)$$

$$\hat{L} = \sqrt{10}\left[d^{\dagger}\times\tilde{d}\right]^{(1)}$$

$$\hat{Q} = \left[d^{\dagger}\times\tilde{s} + s^{\dagger}\times\tilde{d}\right]^{(2)} - \frac{1}{2}\sqrt{7}\left[d^{\dagger}\times\tilde{d}\right]^{(2)}$$

$$\hat{T}_3 = \left[d^{\dagger}\times\tilde{d}\right]^{(3)},\quad \hat{T}_4 = \left[d^{\dagger}\times\tilde{d}\right]^{(4)}$$

Here P is the pairing operator for s and d bosons, Q is quadrupole operator, $\hat{n}_d$ is number of d boson, L is operator of angular momentum, and T_3 octuplet operators and T_4 is hexadecapole operators.

The Hamiltonian starting with U(6) and finishing with group O(2) as given in Equation (2) is bringing to a lower state of three limits, γ-soft O(6), the vibration U(5) and the rotational SU(3) nuclei [17]. We know that in the SU(3) limits, the effective parameter is the quadrupole a_2, in the O(6) limit the effective parameter is the pairing a_0, in U(5) limits, the effective parameter is ε.

The Hamiltonian and eigen-values for the three limits [18]:

U(5):

$$\left.\begin{aligned}\hat{H}_{U(5)} &= \varepsilon\hat{n}_d + a_1\left(\hat{L}\cdot\hat{L}\right) + a_3\left(\hat{T}_3\cdot\hat{T}_3\right) + a_4\left(\hat{T}_4\cdot\hat{T}_4\right)\\ E\left(n_d,\upsilon,L\right) &= \varepsilon n_d + K_1 n_d\left(n_d+4\right) + K_4\upsilon\left(\upsilon+3\right) + K_5 L\left(L+1\right)\end{aligned}\right\} \quad (3)$$

with

$$K_1 = 1/12\,a_1$$

$$K_4 = -1/10\,a_1 + 1/7\,a_3 - 3/70\,a_4$$

$$K_5 = -1/14\,a_3 + 1/14\,a_4$$

O(6):

$$\left.\begin{aligned}\hat{H}_{0(6)} &= a_0\hat{P}\cdot\hat{P} + a_1\hat{L}\cdot\hat{L} + a_3\hat{T}_3\cdot\hat{T}_3\\ E\left(\sigma,\tau,L\right) &= K_3\left[N_b\left(N_b+4\right) - \sigma\left(\sigma+4\right)\right] + K_4\tau\left(\tau+3\right) + K_5 L\left(L+1\right)\end{aligned}\right\} \quad (4)$$

with

$$K_3 = 1/4\,a_0$$

$$K_4 = 1/2\,a_3$$

$$K_5 = -1/10\,a_3 + a_1$$

SU(3):

$$\left.\begin{aligned}\hat{H}_{SU(3)} &= a_1\hat{L}\cdot\hat{L} + a_2\hat{Q}\cdot\hat{Q}\\ E\left(\lambda,\mu,L\right) &= K_2\left(\lambda^2+\mu^2+3\left(\lambda+\mu\right)+\lambda\mu\right) + K_5 L\left(L+1\right)\end{aligned}\right\} \quad (5)$$

with

$$K_2 = 1/2\,a_2$$

$$K_5 = a_1 - 3/8\,a_2$$

K_1, K_2, K_3, K_4, and K_5 are other forms of strength parameters.

Then applying particular limit of symmetry (O(6), SU(3), U(5)) to determine the frame of a set of nuclei is more advantageous than full Hamiltonian of IBM-1. It comprise multi-free parameters those make it simple to fit the structure of a nuclei. A flaw chart of method of calculation is given in **Figure 1**.

3. Results and Discussion

The obtained results have discussed for yrast energy level, γ-band, β-band, effective charge used to reproduce B(E2) values, transition probabilities B(E2), maxing ratio and contour plots of the potential energy surfaces using IBM-1.

The γ-unstable limit has applied for ^{104,106}Ru nuclei using data of experimental energy ratios (E_2: E_4: E_6: E_8 = 1:2.5:4.5:6.5). In the framework of IBM-1, the even

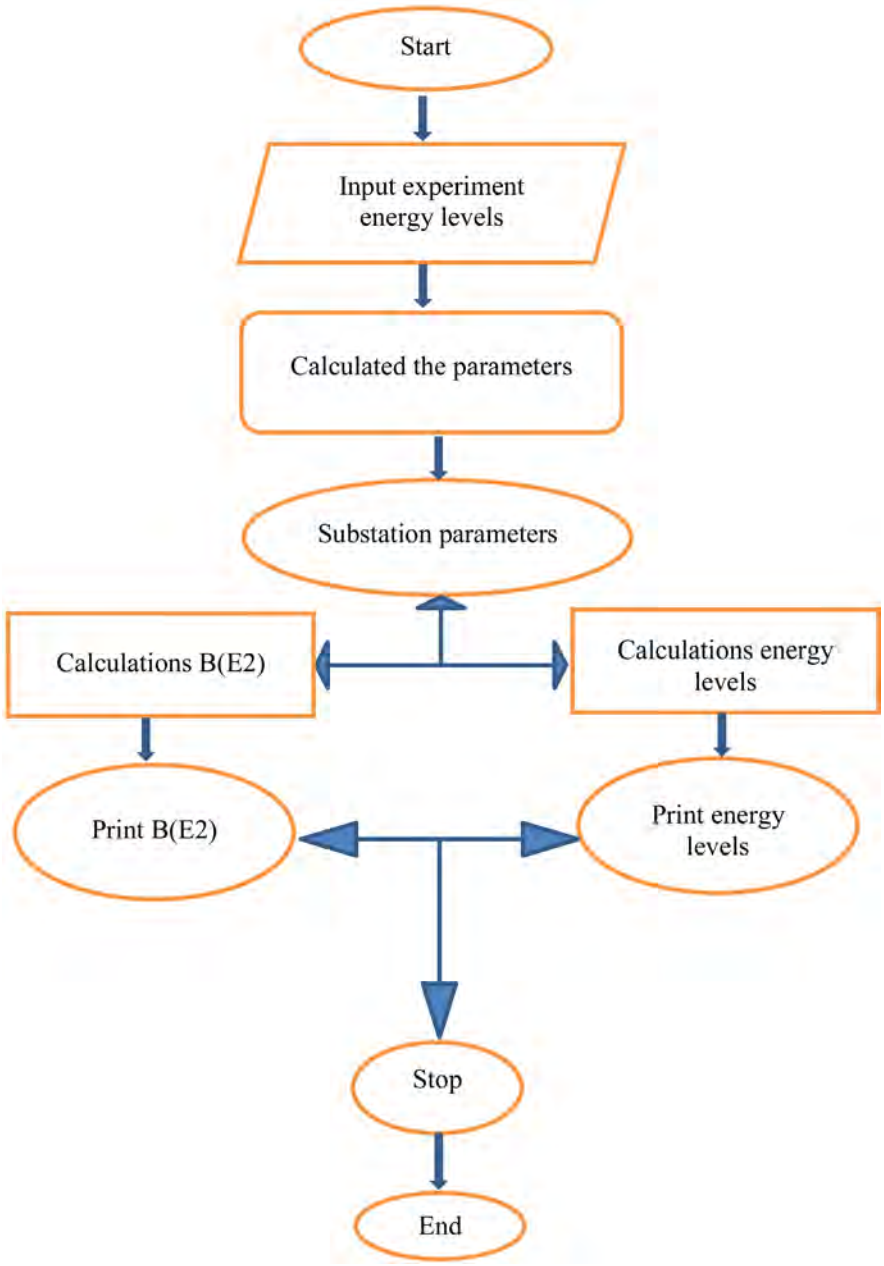

Figure 1. Flowchart of method of calculation.

$^{104\text{-}106}$Ru nuclei have three protons boson hole and five and six neutrons boson particle respectively. Therefore total bosons numbers of ^{104}Ru and ^{106}Ru nuclei are 8 and 9, respectively. The IBM-1 models carry out with no difference between the bosons of proton and neutron. The energy ratio $R = E4_1^+ / E2_1^+$ gives the information of the symmetry shapes of a nucleus. The symbol $E2_1^+$ and $E4_1^+$ is at the energy level 2_1^+ and 4_1^+ respectively. It is known that the $R = E4_1^+ / E2_1^+ \approx 2$ is for U(5), $R = E4_1^+ / E2_1^+ \approx 2.5$ is for O(6) and $R = E4_1^+ / E2_1^+ \approx 3.33$ for SU(3) [19] [20]. The experimental $R_{4/2}$ of ^{104}Ru and ^{106}Ru isotopes is 2.48 and 2.60, respectively. **Figure 2** shows, $R_{4/2}$ values of ^{104}Ru and ^{106}Ru isotopes are O(6) symmetry.

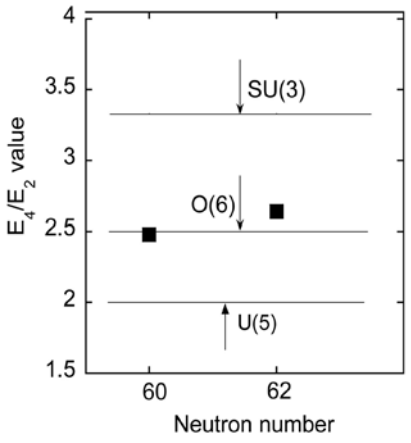

Figure 2. The arrows indicate the line of $\mathrm{E}\left(4_1^+\right)/\mathrm{E}\left(2_1^+\right)$ values of the U(5), O(6) and SU(3) limits. The $\mathrm{E}\left(4_1^+\right)/\mathrm{E}\left(2_1^+\right)$ values of experimental data[22] of the ^{104,106}Ru isotopes are presented as function of neutrons.

The best fit was taken up to 12^+ of Ru isotopes with neutron $N = 60$, 62. The parameters were determined the experimental eigen values ($E(n_d, \upsilon, L)$) from the Equation (4), where n_d, υ and L are quantum numbers. The parameters in the present data are shown in **Table 1**.

The calculated energy levels as well as experimental data are presented in **Table 2**. According to the weight of fitting the Ru-104 and Ru-106 nuclei are good candidates of O(6) symmetry. The calculation of γ-bands and β-bands are compared with experimental data and presented to **Table 3** and **Table 4**. From the tables, the IBM calculations and experimental results are in good agreements [21].

The reduced electric transition probabilities give the more information on the structure of nuclei. The E2 transition operator must be a Hermitian tensor of rank two; consequently, the number of bosons must conserve.

$$T^{E2} = \alpha_2\left[d^\dagger s + s^\dagger d\right]^{(2)} + \beta_2\left[d^\dagger d\right]^{(2)} \tag{6}$$

Here T^{E2} is the operator of reduced matrix elements of the $E2$. ($s^\dagger$, $d^\dagger$) are creation and (s, d) are annihilation operators for s and d bosons. α_2 indicated the effective quadrupole charge and β_2 is dimensionless coefficient, $\beta_2 = \chi\alpha_2$

$$B\left(E2, J_i \to J_f\right) = \frac{1}{2J_i + 1}\left|\left\langle J_f \left| T^{E2} \right| J_i \right\rangle\right|^2 \tag{7}$$

The parameters, α_2 and β_2 of Equation (6), were adjusted to reproduce the experimental $B\left(E2, 2_1^+ \to 0_1^+\right)$. The effective charge ($e_B$) in present calculation is shown in **Table 5**. The values of e_B were estimated to reproduce experimentally $B\left(E2, 2_1^+ \to 0_1^+\right)$. The values $\beta_2 = 0$ for ^{104,106}Ru isotopes because these nuclei have the O(6) property. The calculated values of B(E2) transitions with experimental data are presented in **Table 6** for Ru isotopes with neutron $N = 60$, 62 in this study [21]. The calculated data of IBM-1 is good agreements with the available experimental results.

Table 1. Adopted values for the parameters used for IBM-1 calculations. All parameters are given in MeV, excepted N and CHQ.

A	N	ε	a_0	a_1	a_2	a_2	a_4	$CHQ(\chi)$
^{104}Ru	8	0.000	0.1098	0.0180	0.000	0.1770	0.000	0.000
^{106}Ru	9	0.000	0.0990	0.0102	0.000	0.1513	0.000	0.000

Table 2. g-band (in MeV) for even $^{104\text{-}106}$Ru nuclei.

J^{π}	IBM	Exp.	IBM	Exp.
	^{104}Ru		^{106}Ru	
0^+	0.000	0.000	0.000	0.000
2^+	0.3558	0.3580	0.2726	0.2700
4^+	0.8910	0.8884	0.6570	0.7147*
6^+	1.6056	1.5564	1.1532	1.2958*
8^+	2.4996	2.3204	1.7612	1.9734*
10^+	3.5730	3.1119	2.4810	2.7050
12^+	4.8258	-	3.3126	3.4500*

Table 3. γ-band (in MeV) for even $^{104\text{-}106}$Ru nuclei.

J^{π}	IBM	Exp.	IBM	Exp.
	^{104}Ru		^{106}Ru	
2^+	0.8868	0.8931	0.7256	0.7923
3^+	1.5966	1.2424	1.2610	1.0915*
4^+	1.5990	1.5026	1.3002	1.3068*
5^+	2.4870	1.8723*	1.9082	1.6411*
6^+	2.4906	2.1966*	1.9670	1.9078*
7^+	3.5568	-	2.6672	2.2841*
8^+	3.4878	-	2.7456	2.9600*
9^+	4.8060	-	3.6360	-

Table 4. β-band (in MeV) for even $^{104\text{-}106}$Ru nuclei.

J^{π}	IBM	Exp.	IBM	Exp.
	^{104}Ru		^{106}Ru	
0^+	0.9882	0.9882	0.9900	0.9906
2^+	1.3440	1.5154	1.2626	1.3922
4^+	1.8792	2.0808	1.6470	-
6^+	2.5938	-	2.1432	-
8^+	3.5616	-	2.7512	-
10^+	4.8120	-	3.5380	-

Table 5. Effective charge used to reproduce B(E2) values for even $^{104\text{-}106}$Ru nuclei.

A	N	e_B (eb)
^{104}Ru	8	0.0935
^{106}Ru	9	0.0916

Table 6. Experimental and the IBM-1 values of B(E2) for even $^{104\text{-}106}$Ru nuclei (in e^2b^2).

$I_i \to I_f$	IBM-1	EXP.	IBM-1	Exp.
	^{104}Ru		^{106}Ru	
$2_1^+ \to 0_1^+$	0.1679	0.1682	0.1966	0.1966
$4_1^+ \to 2_1^+$	0.2273	0.2149	0.2689	-
$4_2^+ \to 2_2^+$	0.1282	-	0.1541	-
$6_1^+ \to 4_1^+$	0.2448	-	0.2941	-
$6_2^+ \to 4_2^+$	0.1626	-	0.2000	-
$8_1^+ \to 6_1^+$	0.2384	-	0.2934	-
$10_1^+ \to 8_1^+$	0.2152	-	0.2747	-
$10_2^+ \to 8_2^+$	0.0941	-	0.0000	-
$2_2^+ \to 2_1^+$	0.2273	0.1957	0.2689	-
$4_2^+ \to 4_1^+$	0.1166	-	0.1401	-
$6_2^+ \to 6_1^+$	0.0759	-	0.0933	-
$8_2^+ \to 8_1^+$	0.0000	-	0.0659	-

The application of potential energy surface (PES) gives the information to find microscopic and geometric shapes such as spherical, prolate, oblate and γ independent (γ soft). It gives us about symmetry, the shape of nuclei, the minimum deepness and the change of the shape. The PES of the IBM Hamiltonian was drawn by the Skyrme mean with

$$\left|N,\beta,\gamma\right\rangle = \frac{1}{\sqrt{N!}}\left(b_c^+\right)^N\left|0\right\rangle, \tag{8}$$

$$b_c^+ = \left(1+\beta^2\right)^{-1/2}\left\{S^+ + \beta\left[\cos\gamma\left(d_0^+\right) + \sqrt{1/2}\sin\gamma\left(d_2^+ + d_{-2}^+\right)\right]\right\}, \tag{9}$$

The energy surface $E(N, \beta, \gamma)$ for O(6) limits as a function of β and γ, has been calculated [1] [22]. Here, β were indicated the total deformation of a nucleus. **Figure 3** shows the contour plots in the γ-β plane resulting from $E(N, \beta, \gamma)$ for ^{104}Ru and ^{106}Ru isotopes. The potential surfaces are approximately independent of gamma only. In this figure, the color lines show the values of the potential energy surface in MeV. The mapped IBM energy surfaces of ^{104}Ru and ^{106}Ru are O(6) characters.

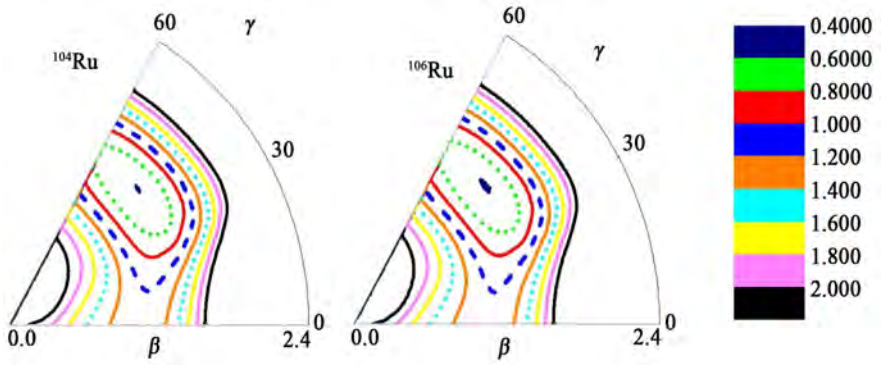

Figure 3. Contour map of potential energy surfaces for Ru isotopes with $N = 60, 62$.

4. Conclusion

The yrast band, gamma band and beta band, electromagnetic transition and potential energy surface of ^{104}Ru and ^{106}Ru isotopes calculated in terms of O(6) limit of interacting boson model-1. The energy levels up to 12^+ of ^{104,106}Ru nucleus found by the best fitted of the parameters in the Hamiltonian of the IBM-1. The analyses of the IBM-1 results for the ground state band suggest a satisfactory agreement with the experimental data. The nobility and contribution of this work included that the framework of interacting boson approximations shows the Ru with neutron numbers 60 and 62 considered gamma soft O(6) symmetry.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nucleus Directs the Electronic Structure of the Atom

Faustino Menegus

Viale Europa 15, Bussero (MI), Italy
Email: menegus.faustino@gmail

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Abstract

The present study supports the provocative idea that the nucleus directs the atom's electronic structure. With the progress of the atomic number the Atomic Molar Volume evolution of the chemical elements obeys the atom's electronic structure rules, fitting at the same time the concomitant specular evolution of the Neutron Excess addition to the nuclei. Details such as the Atomic Molar Volume contraction of the d blocks transition metals or of the Eu and Yb atomic volume anomaly of the lanthanoid metals respond to the nuclear in addition to the atom's electronic structure. Atom's nuclei are synthetized in the star interior and capture the electrons only after migration to the star's periphery, to become stable atoms: nuclei are prior to atoms. Nuclear structure elements, like the 50 and 82 neutron and proton magic numbers, are geared to the noble gases, the central elements of the electronic structure.

Keywords

Atom's Structure, Nuclear Structure, Electronic Structure, Neutron Excess

1. Introduction

The correlations existing between the atom's nuclear and electronic structure, whereby the nuclear structure directs the electronic one, were proposed in two different studies by the present author [1] [2]. In addition, starting from completely independent considerations, identical suggestions were advanced by two other authors [3] [4]. The aim of the present paper is to provide further support to the title statement, considering the evolution of the Atomic Molar Volume (AMV) with the progress of the chemical elements atomic number (**Figure 1**). The AMV outline and periodicity are beautifully explained by the atom's electronic structure, with the aid of the s, p, d and f orbital structure, multiplicity, spatial orientation and order of filling by the electrons [5]. It will be shown here that the

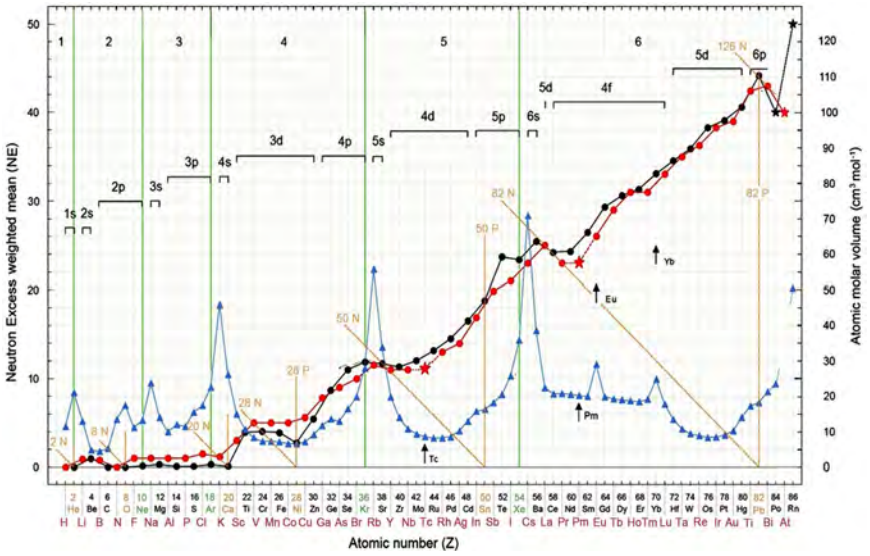

Figure 1. The representation of the Elements NE weighted means and of the Elements Atomic Molar Volumes. The noble gases limiting the periods of the periodic table, indicated at the top of the figure, are green; s, p, d, f, indicate the electron's angular momentum quantum numbers. Highlighted are the proton-neutron couples of the nuclear magic numbers. The NE means are black or red for even or odd Elements respectively. (▲) indicate the Atomic molar Volume. (★) indicate the most stable isotope of the artificial elements.

evolution mode of the Neutron Excess (NE) addition to the nuclei can faithfully explain the AMV outline in the periods 4, 5 and 6 of the periodic table as can be readily perceived from Figure 1. See discussion for periods 2 and 3. Even details such as the U shaped AMV contraction of the d blocks transition metals or the sudden AMV expansion of Eu and Yb, inside the lanthanoid metals of the 4f block, can find a convincing interpretation by the NE addition mode to the nucleus. To deal with the electronic structure of the atom it is mandatory to enter the world of chemistry.

A problem of semantics must be stressed here. The definition of the atom's electronic structure as the atomic structure is a misdefinition. It is at the origin of the nuclear and atomic definition of the two branches of physics. Atomic physics should be reserved to the physics of the whole atom in spite of the historical definitions originated at the time of the Bhor atom.

2. Methods

The isotopes of any chemical element can be defined in equivalent ways by couples of two numbers added to the element symbol: ${}_{Z}X^{A}$; ${}^{A}X^{N}$; ${}_{Z}X_{NE}$. Z, A, N, NE, indicate the proton number, Mass, the Neutron and the Neutron Excess numbers respectively of an isotope. In the present paper the third way is choosed, with NE = A − 2Z, allowing the isotope representation in the Z, NE plane. The mass numbers A were obtained from Tuli, as well as the mass excess values for the nuclear reactions, expressed in MeV [6]. The result is a new method for the representation of the chemical elements isotopes [7].

3. Results

In Figure 1 the by far large AMV expansion corresponds to the electron filling of the s orbital couples marking the table periods opening and their closing by the noble gases. Inside the s orbital couples the NE addition to nuclei is similar. It is practically null for the 1 to 3 s orbital couples, see discussion, but strongly increases with the nuclear mass and size increase of the 4, 5 and 6 s orbital couples.

The electron filling of the 4, 5 and 6 p orbitals, marked by a sharp expansion of the AMV, is accompanied by a corresponding specular increase of the NE addition to nuclei. See the discussion for the very low or null NE addition to the nuclei for the 2p and 3p orbitals, nevertheless associated with a sharp AMV expansion.

A net AMV contraction accompanies the electron filling of the 3, 4 and 5 d orbitals in spite of the progressive NE addition to the nuclei. The AMV contraction of the d blocks metals shows in all instances a characteristic U shaped outline. A general AMV contraction accompanies again the electron filling of the 4f orbitals, in spite of a sustained NE addition to nuclei. However, in the Eu and Yb instance a sudden AMV expansion replaces the contraction. The electron filling of the d and f orbitals always anticipates that of the p orbitals of the same period.

The 50 and 82 neutron magic numbers cross the ^{86}kr and ^{136}Xe isotopes at the upper border of the beta stability valley (Figure 2), thus extending the partial gearing of the 50 and 82 proton magic numbers with the Xe and Rn noble gases [2].

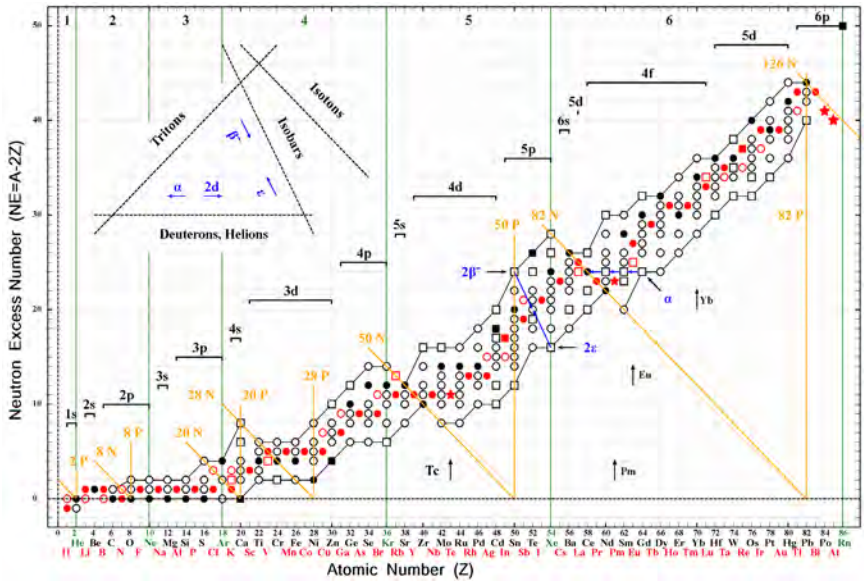

Figure 2. Representation of the Elements isotopes by the Neutron Excess number, NE = A − 2Z, in the Z-NE plane and the respective electronic structure. Other indication as in Figure 1. Even and odd Element's symbols are black and red respectively; (○) (□) represent stable and radioactive isotopes respectively, with the full symbol indicating the most abundant isotope of each Element; (★) represents the most stable isotope of the artificial Elements. The inset shows basic relationships between the isotopes along with radioactive decay paths.

4. Discussion

The salient features of the Atomic Molar Volume (AMV) expansion outline will be first considered from the atom's electronic structure and, subsequently from the accompanying nuclear events point of view.

The table periods opening, behind their closure by the noble gases, entails the progress of the electronic principal quantum number. The ensuing electron filling of the s spherical orbitals causes, as accepted [5], the largest increase of the atom's radius and volume: the AMV expansion is essentially of electronic origin. The increasingly large NE addition to the nuclei in the 5, 6 and 7 s orbitals indicates a concerted action of the electronic and nuclear structures in the related AMV expansion. See below for the lack of NE addition in the 1 to 3 s orbitals.

The most important news of **Figure 1** concerns the sequence of the electron filling of the p, s and d or f orbitals. Not only that sequence parallels the NE addition to nuclei but it is also related to the nucleus by the 50 and 82 neutron magic isotons. That is the noble gases and the alkaline and alkaline earth metals, at the heart of the atom's electronic structures, are patently related to the nuclear structure.

Inside the periods the AMV expansion may be still important but always at a lower rate compared to the effects of the increase of the electron principal quantum number. An AMV expansion occurs accompanying the electron filling of the three p orbitals by six electrons. Since the p electrons distribute only radially along the x, y and z atom's Cartesian coordinates they will cause a considerable radius and AMV expansion of the atom. To that AMV expansion corresponds a sustained increase of the NE addition to the nuclei in the 4, 5 and 6 periods: again a concerted action of the nuclear and electronic structures. Yet this is not true for the periods 2 and 3 where to the AMV expansion the NE addition to nuclei is practically null. As already suggested [2] this may be the result of the different mechanisms of nucleosynthesis: nuclear fusion for the elements up to Fe then followed by the neutron capture mechanism [8]. A very different suggestion may be advanced. High levels of the ^{40}Ar neutron rich isotope, 1% only of the solar system Ar abundance, may be synthetized in the star's interior to be subsequently depleted as neutron sources for nucleosynthesis, always in the star's interior, as in the reaction below:

$$^{52}\mathrm{Fe} + {}^{40}\mathrm{Ar} = {}^{54}\mathrm{Fe} + {}^{38}\mathrm{Ar} + 7.595\ \mathrm{MeV}$$

An event very difficult to ascertain since totally confined in the star's interior.

At variance with the p, the electron filling of the d orbitals is accompanied by a sharp AMV contraction, the characteristic of the d metals blocks transitions in chemistry. The five d orbitals hosting ten electrons, compared to the p orbitals, distribute more evenly around the nucleus with a better spatial utilization of the atom's volume. This is likely the most important reason of the AMV contraction of the d transition metals. In addition, the d are spatially internal to the p orbitals and border the huge AMV expansion of the s orbitals elements. This last situation, together with the volume expansion caused by the half and complete filling

of the d blocks, confer the typical U shaped outline of the AMV contraction of the d metal blocks (**Figure 1**). Interestingly Sc, Y, La and Zn, Cd, Hg, the elements opening and closing respectively the d blocks, show chemical properties very different compared to the properties of the internal d blocks metals [5]. From the nuclear structure point of view the NE level appears more elevated at the borders, see in particular Zn, compared to the central elements of the d blocks, (**Figure 1** and **Figure 2**). The nuclear works in concert with the atom electronic structure.

The AMV contraction, following the electron filling of the 4f orbitals again ascribes to geometric reasons. The 4f seven orbitals distribute spatially around the nucleus even more evenly compared to the d orbitals [5], thus granting the allocation of fourteen electrons without a major expansion of the atomic radius and of the AMV. From the electronic structure side, the AMV anomalous expansion of Eu and Yb is caused by the sudden increase of their atomic radius, in his turn caused by the half and complete filling of the f block orbitals [5]. In chemistry, these metals appear therefore as Eu^{++} and Yb^{++} ions, at variance with the oxidation numbers X^{+++} of the bulk lanthanoid metals [9]. The rather sudden EN addition to nuclei indicate that in Eu and Yb anomaly the nuclear and the electronic structures of the atom work in concert (**Figure 1** and **Figure 2**).

A partial gearing of elements of the nuclear and electronic structures may be found in the four proton identical gap between the 50 and 82 proton magic numbers and the noble gases Xe and Rn respectively. The same applies to the seven proton identical gap from Kr and Xe to the unstable nuclei of Tc and Pm respectively [2]. The 50 and 82 neutron magic isotons, crossing the upper border of the beta stability valley at the noble gases ^{86}Kr and ^{136}Xe isotopes, considerably extends the above gearing (**Figure 2**). An important share of the periodic table, from Kr to Rn, appears somehow geared to nuclear structure.

5. Conclusion

The AMV expansion, when electrons increase the atom's radius and volume as in the case of the s and p orbitals or in the case of the Eu and Yb 4f orbitals, is patently clear. The same is true in the case of the AMV contraction when electrons dwell in spaces internal to the p orbitals. What, at present, is obscure is how the NE addition to the nuclear structure, concomitant with the above events, can affect the atomic radius and volume, typical properties of electronic structure. The answer may likely be in the electrostatic and electromagnetic interactions between the two main atom's compartments [10].

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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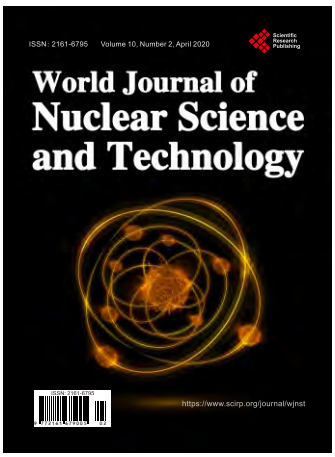

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