RECENT BASIC ADVANCES OF NEUTRON ACTIVATION ANALYSIS

Nikhita M. Chambhare[1], Shailesh D. Ghaywat[2], Milind J Umekar[2]and R. T. Lohiya[*1]

[1]Department of Pharmaceutical Chemistry, Smt. Kishoritai Bhoyar College of Pharmacy, Kamptee, Nagpur (M.S)-441002, India.
[2]Department of Pharmaceutics,Smt. Kishoritai Bhoyar College of Pharmacy, Kamptee, Nagpur (M.S)-441002, India.

* Corresponding Author. E-mail: rtlohiya@gmail.com

ARTICLE INFO	ABSTRACT
	Neutron activation analysis (NAA) is an specific analytical technique for the quantitative and qualitative measurement of chemical elements. The method is based on the conversion of stable atomic nuclei into the radioactive nuclei by irradiation with neutrons and the subsequent detection of the radiation emitted during the decay of these radioactive nuclei. NAA is today rather rapidly progressing from a stage of extensive exploration and development in relatively specialized laboratories to a stage of increasingly common application to a wide variety of research activities in many laboratories. Due to their high accuracy and reproducibility, different types of NAA are being used in various studies and in application for the determination of concentration of elements down to the trace and ultra-trace level. The review mainly focused on various application of NAA like Human sample analysis, in Medicine, in Radiotraces and Geological samples are briefly characterized in order to depict the information.

INTRODUCTION

Analytical science to develop the methodology for the investigation of properties and structure of matter at level of single nucleus, atom and molecule, and scientific analysis to figure out either chemical composition or elemental contents in a sample are indispensable in basic research and development, as well as in industrial applications [1]The discovery of the artificial radioactivity by Irene Curie and Frederic Joliot in 1934 motivated many physicists and chemists to perform experiments where stable nuclides convert into radioactive after irradiation with alpha particles, protons and therefore the recent discovered neutron (1932).

In (1936) Hilde Levi andGeorge de Hevesy used for thefirst-time nuclear reactions after irradiation with neutrons for elemental analysis. They worked at that time in the Niels Bohr headed Institute for Theoretical Physics at the University of Copenhagen. The idea of George de Hevesy was very simple: he used the correlation between the stable initial nuclides and the produced number of radioactive nuclides in order to obtain qualitative and quantitative chemical analysis of the chemical elements which belong to the initial products. The available neutron fluxes were small at that point and therefore the identification of the obtained radionuclides was possible because of their different half-life times only. In spite of this the primary example showed successful analysis of 1% Chronicles Dysprosium in Yttrium sample after bombardment with neutrons. After World War IInuclear reactors with neutron flux densities in order of magnitude of 10^{12} cm^{-2} s^{-1} became available which allowed for

9873

achieving a detection limit for certain elements below 1 µg. This opened new research fields in solid state physics where the properties of the materials as a function of their impurity were investigated. The development of the methodological procedures and high-resolution gamma-spectrometry detectors enable nowadays to research simultaneously up to 50–60 elements during a single sample.[2]In spite of the developments in other chemical techniques, the simplicity and selectivity, the speed of operation, the sensitivity and accuracy of NAA became and maintained its role as a powerful analytical technique.

Currently, there are many elemental analysis methods that use physical, chemical and nuclear characteristics. However, a selected method could also be favoured for a specific task, counting on the aim. Neutron activation analysis (NAA) is extremely useful as sensitive analytical technique for performing both qualitative and quantitative multielemental analysis of major, minor and traces components in sort of terrestrial samples and extra-terrestrial materials. In addition, thanks to its accuracy and reliability, NAA is typically recognized because the "referee method" of choice when new procedures are being developed or when other methods yield results that do not agree.It is usually used as a crucial reference for other analysis methods. Worldwide application of NAA is so widespread it's estimated that approximately 100,000 samples undergo analysis annually. [3]

NAA can also be used to detect trace element in water, biological, material and minerals. In archaeology, NAA can give useful information about the origin of the findings consistent with the so-called "fingerprint" of the individual element composition in their raw materials. It is usually used as a crucial reference for other analysis methods. NAA can detect up to 74 elements depending on the experimental procedure, with minimum detection limits ranging from 10^{-7} to 10^{-15} g/g, depending on the elements and matrix materials. Some nuclei can capture variety of neutrons and remain relatively stable, not undergoing transmutation or decay for several months or maybe years. Different various

nuclei have different cross sections and half-lives, and thus the intensities of the emitted gamma-rays can also vary therefore the detection limits are quite variable. Rare earth elements (REE) have very high thermal neutron cross sections and NAA is typically the primary choice for the determination of REEs during a trace elements analysis. By using the automated sample handling (e.g., element using rabbit system), gamma-ray measurement with solid-state detectors, and computerized processing is generally possible to simultaneously measure more than thirty elements in most sample types without chemical processing. The application of purely instrumental procedures is commonly called instrumental neutron activation analysis (INAA) and is one of NAA's most important advantages over other analytical techniques, especially in the multi- analysis. If chemical separations are done to samples after irradiation to get rid of interferences or to concentrate the radioisotope of interest, the technique is named radiochemical neutron activation analysis (RNAA). The latter technique is performed infrequently thanks to its high labour cost.

The Major Advance in the NAA method in the year 1936-1944, the development of the great potential of the NAA method was limited and relatively slow, owing to lack of high-flux neutron sources and lack of gamma-ray spectrometry equipment. With the arrival of charged-particle accelerators (cyclotrons, Cockcroft-Walton accelerators, and Van de Graaff accelerators) within the 1930s, charged particle activation analysis (CPAA) became possible, but the absence of gamma-ray spectrometry equipment was still a severe limitation. In this early period, the NAA of multielement samples had to be conducted via tedious, though elegant, post irradiation radiochemical separations with carriers.

In the year 1970, During this period, no spectacular new advances in the capabilities of the NAA method have occurred. The competition from nonnuclear methods of trace element determinations that have advanced rapidly during this period: particularly methods such as atomic absorption spectrophotometry (AAS) and inductively-coupled plasma (ICP) atomic emission

9874

spectroscopy. The NAA method (utilizing reactor fluxes of thermal neutrons) was essentially the sole sensitive, quantitative, multielement analytical method available up to the mid-1960s, but it now must compete increasingly with methods such as AAS and ICP. The NAA method, and particularly its INAA form, still has advantages over these other methods for several specific analytical problems, but its need to be used of an upscale device--a nuclear reactor may be a barrier to several analytical chemists preferring to be ready to do their analyses in their own laboratory, using less costly equipment. Many NAA groups, make effective use of nearby nuclear reactors that they do not own [4]

PRINCIPLE OF NAA:
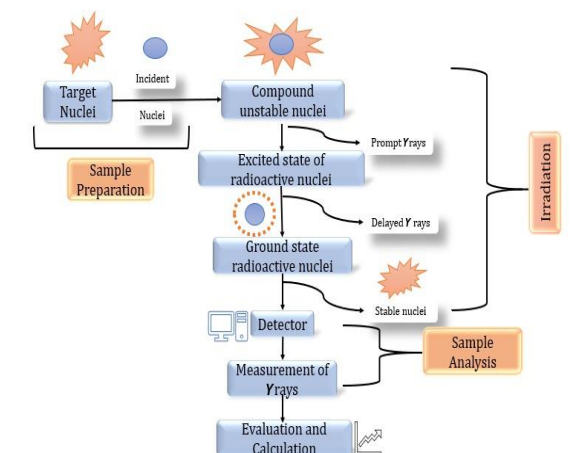
Fig 1: Principle of Neutron Activation Analysis (NAA)

The activation of samples will end in a mix of activities, which may be analysed for individual contributions by two approaches:

i. Destructive or Radiochemical Neutron Activation Analysis: The resulting radioactive sample is decomposed, and through chemical separations it's divided into fractions with a few of elements each.

ii. Non-destructive or Instrumental Neutron Activation Analysis: The resulting radioactive sample is kept intact, and therefore the elements are determined by taking advantage of the differences in decay rates via measurements at different decay intervals utilizing a equipment with a high energy resolution.[1]

Activation

The activation with neutrons is, upon preparation of the test portion, the primary stage in an INAA procedure. Each atomic nucleus can capture a neutron during irradiation, resulting in a nuclear reaction in which often the nuclear mass changes; immediately (typically 10^{-14}s) after the capture ('promptly') excess energy within the sort of photons and/or particles are going to be emitted. The newly formed nucleus if remains unstable, then it starts already during the activation decaying to a stable state by the emission of radiation through one or more of the following processes: α-decay, β–decay, electron capture, β+-decay, or internal transition decay. In most cases γ- and X-radiation.

Neutrons are produced in: –

Isotopic neutron sources, like 226Ra (Be), 124Sb (Be), 241Am (Be), 252Cf.

- Particle accelerators or neutron generators. The most common types are supported the acceleration of deuterium ions towards a target containing either deuterium or tritium, leading to the reactions 2H (2H, n)3He and 3H (2H, n)4He, respectively.
- Nuclear research reactors. These are the strongest sources of neutrons. The neutron output of research reactors is usually quoted as flux in an irradiation facility and varies, counting on reactor design and reactor power, between 10^{11} and 10^{14} cm^{-2} s^{-1}.

In the majority of INAA procedures reactor neutrons are used for the activation. Materials are often activated in any physical state, viz. solid, liquid or gaseous. There is no fundamental necessity to convert solid material into a solution before activation; INAA is actually considered to be a non-destructive method although under certain conditions some material damage may occur thanks to thermal heating, radiolysis and radiation tracks by e.g., fission fragments and α-radiation emitting nuclei.

Decay

Radioactive decay may be a statistically random process; the probability that a given nucleus will decay during a certain interval depends only of the time of observation. It is impossible to predict when a given nucleus will decay, but the decay characteristics are

9875

often described by the physical laws of decay whereas documented decay schemes provide the small print of the decay of radionuclides, such as, e.g., half-lives involved, sorts of radiation emitted and relative intensities.

Measurement

In NAA, nearly exclusively the (energy of the) gamma-radiation is measured due to the penetrating power of this sort of radiation, and therefore the selectivity which will be obtained from the distinct energies of the photons. The produced gamma-spectrum is analysed to identify the radionuclides and their amounts of induced activity in order to derive the target elements from which they have been produced. The masses of the weather are derived from internet peak areas by comparison with the induced activity of an equivalent neutron activation produced radionuclides from known amounts of the element of interest in the calibrator. The relative intensities if photons of various energies are emitted, the combination of energy of emitted radiation and therefore the half-life of the radionuclide is exclusive for every radionuclide, and forms the idea of the qualitative information in NAA.[2]

In principle, with reference to the time of measurement, NAA falls into two categories:

1) prompt gamma-ray neutron activation analysis (PGNAA), where measurements take place during irradiation.

2) delayed gamma-ray neutron activation analysis (DGNAA), where the measurements follow decay.

The PGAA technique is usually performed by employing a beam of neutrons extracted through a reactor beam port. Fluxes on samples irradiated in beams are within the order of 1 million times less than on samples inside a reactor but detectors are often placed very on the brink of the sample compensating for much of the loss in sensitivity. This technique is most applicable to elements with extremely high neutron capture cross-sections (B, Cd, Sm, and Gd); elements which decay too rapidly to be measured by DGAA; elements that produce only stable isotopes (e.g., light elements); or elements with weak decay gamma-ray intensities. 2D, 3D analysis of (main) elements distribution within the samples is often performed by PGAA.

DGNAA (sometimes also called as conventional NAA) is useful for the vast majority of elements that produce radioactive nuclides. The technique is flexible with regard to time such the sensitivity for a long-lived radionuclide that suffers from interference by a shorter-lived radionuclide are often improved by expecting the short-lived radionuclide to decay or quite the contrary, the sensitivity for short-lived isotopes is often improved by reducing the time irradiation to attenuate the interference of long-lived isotopes. This selectivity may be a key advantage of DGNAA over other analytical methods. [3]

PROCEDURE:

In the most of INAA procedures reactor neutrons are used forthe activation: neutrons in equilibrium with their environment. Sometimes activation with epithermal reactor neutrons (neutrons within the method of slowing down after their formation from fission of 235U) is preferred to strengthen the activation of elements with a high ratio of resonance neutron cross section over thermal neutron cross section relatively to the activation of elements with a lower such a ratio. in theory materials are often activated in any physical state, viz. solid, liquid or gaseous. there's no fundamental necessity to convert solid material into a solution before activation; INAA is really considered to be a non-destructive method although under certain conditions some material damage may occur due to thermal heating, radiolysis and radiation tracks by e.g., fission fragments and α-radiation emitting nuclei. it's essential to possess quite two or three qualified full-time members of the staff with responsibility for the NAA facilities. they ought to be able to control the counting equipment and have good knowledge of basic principles of the technique. additionally, the facility users and thus the operators must establish an honest channel of communication. Other support staff are getting to be required to require care of and improve the equipment and facility. It seems; therefore, a multi-disciplinary team could run the NAA system well. [3]

The analytical procedure is based on four steps:

Step 1: sample preparation (figure 1) means in most cases only heating or freeze drying, crushing or pulverization, fractionating or pelletizing, evaporation or pre-concentration, put through a sieve, homogenising, weighing, washing, check of impurities (blank test), encapsulation and sealing irradiation vial, also because the choice of the only analytical process and thus the preparation of the standards. The laboratory ambiance is additionally important for preservation and storage of the samples. Standardization is that the idea permanently accuracy of analytical tools and sometimes depends on particular technology, facility and personnel. For production of accurate data, careful attention to all or any or any possible errorin preparing single or multi-element standards is significant, and standards must be chosen relying on the character of the samples

Step 2: Irradiation of samples are often taken from the varied sorts of neutron sources consistent with need and availability. For the INAA, one pneumatic transfer system installed within the horizontal channel at Es-Salam research reactor for brief irradiation of samples. Additionally, two vertical channels located in several sites of the deuterium oxide moderator and therefore the graphite reflector are used for long irradiations. The neutron spectrum parameters at different irradiation channels like α, f, Tn, etc are experimentally determined using cadmium ratio, cadmium cover, bare triple monitor and bi-isotopic methods using HΦgdhal convention and Westcott formalism. (Table1 and Table 2) The calibration of the irradiation positions has been achieved to implement the k0 -NAA in our laboratory.

Step 3: After the irradiation the measurement is performed after an appropriate cooling time (t_c). In NAA, nearly exclusively the (energy of the) gamma ray is measured due to its higher penetrating power of this sort of radiation, and therefore the selectivity which will be obtained from distinct energies of the photons differently from β radiation which is a continuous energy distribution. The interaction of gamma- and X-radiation with matter results, among others, in ionization processes and subsequent generation of

electrical signals (currents) which will be detected and recorded. The instrumentmeasures the gamma rays from radioactive samples generally consists of a semiconductor detector, associated electronics, and a computer-based multi-channel analyser (MCA/computer).

Most NAA labs operate one or more hyper-pure germanium (HPGe) detectors, which operate at nitrogen temperature (77 K). Although HPGe detectors are available many various shapes and sizes,the foremost common shape is coaxial. These detectors are very useful for measurement of gamma rays with energies within the range from about 60 keV to 3.0 MeV. The two most vital characteristics a HPGe detector are its resolution and efficiency. Other characteristics to think about are peak shape, peak-to-Compton ratio, pulse rise time, crystal dimensions or shape, and price. The detector's resolution may be a measure of its ability to separate closely spaced peaks within the spectrum, and, generally, the resolution is laid out in terms of the complete width at half maximum (FWHM) of the 122 keV photopeak of 57Co and therefore the 1,332 keV photopeak of 60Co. In most of the NAA applications, a detector with 0.5 keV resolution or less at 122 keV and 1.8 keV or less at 1,332 keV is sufficient. Detector efficiency for a given detector depends on gamma-ray energy and therefore the sample and detector geometry, i.e., subtended angle. At Es-Salam NAA Lab, four gamma-ray spectrometers of Canberra that one among them consists of a HPGe detector 35% relative efficiency connected with Genie 2k Inspector and therefore the three other spectrometers are composed of detectors (30, 35 and 45 relative efficiency) connected with a 3 Lynx® Digital Signal Analyser, it's a 32K channel integrated signal analyser based on advanced digital signal processing (DSP) techniques. All spectrometers operate with Genie™2000 spectroscopy software. A radiation detector therefore consists of an absorbing material during which a minimum of a part of the radiation energy is converted into detectable products, and a system for the detection of these products.

9877

Step 4: Measurement, evaluation and calculation involve taking the gamma spectra and therefore the calculating chemical element concentrations of the sample and preparation of the NAA report. In this part of work, Peter Bode describes clearly in his paper Greenberg, R.R., et al., the analysis procedure of gamma-spectrum to the determination of the amount of element in sample. The acquisition of gamma spectrum via the spectroscopy system is analysed to identify the radionuclides produced and their amounts of radioactivity in order to derive the target elements from which they need been produced and their masses within the activated sample. The spectroscopy starts with the determination of the situation of the (centroids of the) peaks. Secondly, the peaks are fitted to get their precise positions and net peak areas. The Analytical protocol adopted in our NAA laboratory.

The positions often expressed as channel numbers of the memory of a multi-channel pulse height analyser are often converted into the energies of the radiation emitted; this is often the idea for the identification of the radioactive nuclei. On basis of data of possible nuclear reactions upon neutron activation, the (stable) element composition springs. The values of internet peak areas are often wont to calculate the amounts of radioactivity of the radionuclides using the complete energy photopeak efficiency of the detector. The amounts (mass) of the weather may then be determined if the neutron fluence rate and cross sections are known. In the practice, however, the masses of the weather are determined from internet peak areas by comparison with the induced radioactivity of an equivalent neutron activation produced radionuclides from known amounts of the element of interest. The relative intensities if photons of various energies are emitted, the combination of energy of emitted radiation and therefore the half-life of the radionuclide is exclusive for every radionuclide, and forms the idea of the qualitative information in NAA. The amount of the radiation is directly proportional to the number of radioactive nuclei produced (and decaying), and thus with the number of nuclei of the stable isotope that underwent the nuclear reaction. It provides the quantitative information in NAA. The measurement in NAA is the quantity intended to be measured is the total mass of a given element in a test portion of a sample of a given matrix in all physicochemical states. The quantity 'subject to measurement' is that the number of disintegrating nuclei of a radionuclide. The measurement leads to the number of counts during a given period of your time, from which the disintegration rate and therefore the number of disintegrating nuclei is calculated; the latter number is directly proportional to the number of nuclei of the stable isotope subject to the natural process, and thus to the number of nuclei of the element, which finally provides information on the mass and amount of substance of that element.

ADVANTAGES:

The method Neutron Activation Analysis has several important advantages as follows: -

1. Nuclear technique which measures the intensity of gamma rays ofcharacteristicenergy using the gamma ray spectroscopy.

2. This technique is MultielementalAnalysis.

3. Rapid analyses of multiple samples.

4. Sample size can be varied (typically 1 mg to 1 gm).

5. The Neutron Activation Analysis is very useful for analysis of materials for the purpose of preparing the reference standards.

6. It is Non-destructive, that is valuable and safe.

7.In this process the chemical processing is not occurred, therefore, samples are not contaminated during sample preparation, no uncertainty about total dissolution of sample, no need of dilutions to the solutions and thus making the technique safe and valuable.

8. No need for repeated blank measurements because of no memory effects.

9. Gamma ray spectroscopy is completely free from matrix interferences.

10. Elemental concentrations can be determined in parts per million (ppm), parts per billion (ppb) and parts per trillion (ppt) level, depending upon the sample matrix[5]

DISADVANTAGES:

Neutron activation analysis has its certain disadvantages, and it is divided into three classes: Chemical, physical and Nuclear.[6]

9878

Chemical

1. Samples may undergo structural changes as a result of high radiation intensities, and these changes may result in losses of radioactive material by volatilization.

2. Some limitations arise in separating the desired activity from other radioactive elements in the samples, the magnitude of these limitations depending on the number of steps in the radiochemical procedure used.

3. It is not always easy to treat the samples in such manner that the carrier element and the irradiated element will chemically behave the similar.

Physical

1. A sample must be of such character as to withstand temperatures of possibly 700°C to 900°C.

2. Containers must be constructed of such material that during irradiation, they must have very short half-lives.

3. The size of the samples should be limited by the irradiation space in a reactor.

Nuclear

1. The samples must not have such a high neutron absorption as to affect the neutron flux throughout the samples.

2. A major limitation is that the isotope formed may be the result of neutron reactions other than an (n, y) reaction.

3. Of some importance is the formation of radioisotopes of the same element differing from the isotope under investigation as a result of the decay of other radioactive species. However, this limitation may be overcome by determining decay and energy of emission.
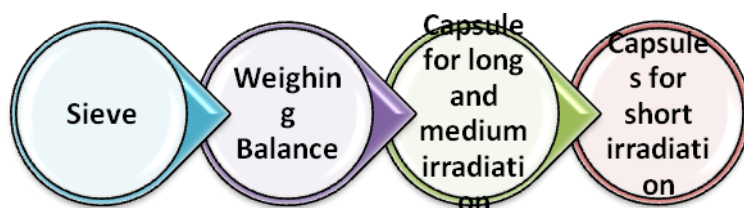
**Figure 2**: Instruments and materials used for preparation of sample

Table 1- The parameters α, f and r(α)√Tn/To obtained by different methods

Method	A	F	r(α)√Tn /To
Cd-ratio	0.026±0.012	28.4±1.6	0.038±0.004
Cd-covered	0.024±0.010	28.7±2.1	-
Bare triple monitor	0.030±0.008	28.6±1.8	-
Bare bi-isotopic	-	29.5±2.5	0.036±0.003
Average	0.027±0.010	28.8±2.0	0.037±0.003

Table 2- Neutron spectrum parameters in the irradiation site at Es salam research reactor

Parameter	A	F	Tn(∘c)	Rcd (Au)	r(α)√Tn/To
Measured Value	0.027±0.010	28.8±2.0	34±1.8	2.93±0.32	0.037±0.003

TYPES OF THE NEUTRON ACTIVATION ANALYSIS:
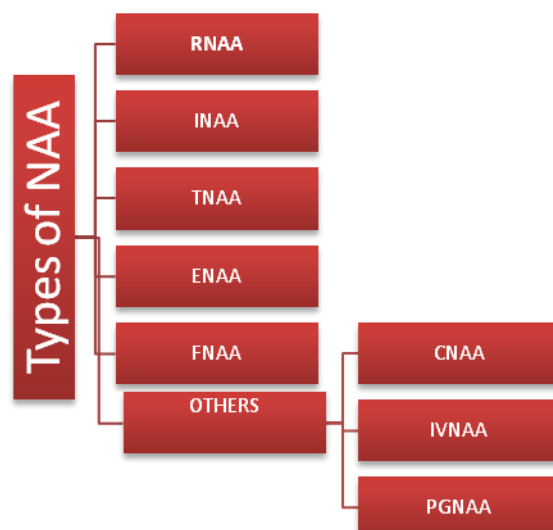
Figure- 3 Different Types of Neutron Activation Analysis

1]Radiochemical neutron activation analysis (RNAA)

RNAA is used within the case where the induced radionuclides of trace elements are masked by matrix activity. The resulting radioactive sample is chemically decomposed and therefore the radionuclides are isolated by chemical separations into one or several fractions freed from interfering radio activities, each with one or relatively few radionuclides. the foremost frequently used separation techniques are: liquid extraction,[7][8]ion exchange, [9][10]precipitation,[11, 12]Electrolysis[13]and chromatography[14]. Generally, a carrier is added during the chemical separation. consistent with IUPAC, a carrier is an inactive material deliberately added to a specified radioactive substance to make sure that the radioactivity will behave normally altogether subsequent chemical and physical processes.Before separation, samples need to be chemically decomposed. Usuallyvarious acids (HNO_3, H_2SO_4, HF, $HClO_4$) are used for digesting the sample or burnt in an oxygen atmosphere. Although RNAA has the advantage of high sensitivities to several elements and therefore the obtained data are accurate. Thistechnique has two disadvantages: it's rather time consuming and therefore the radiochemical procedures can often be very complicated.[10]

2] Instrumental neutron activation analysis (INAA)

When applying instrumental neutron activation analysis (INAA)[15,16,2,17,18]the decomposition of the radioactive sample isn't necessary. The radionuclides are determined on the thought of the differences in decay rates via measurements at different decay intervals using high-resolution detectors, the method is non-destructive. It doesn't require complicated handling.All problems associated with the decomposition of the sample and separation (dissolution, contamination and losses) are avoided. This aspect is extremely important when unique or valuable materials must be analyzed, e.g., archaeological and art objects or within the case of materials that are difficult to dissolve, e.g., silicon-based samples or ceramics. It's multielemental, suitable for sample sizes from µg to kg, which allows one to get low detections limits (at µg/kg to mg/kg level) for up to fifty elements. Various amounts of elements from sub-ng/g up to a quarter level give linear responses. Better detection limits of desired elements are often achieved by optimizing irradiation parameters (energy, fluence rate of the neutrons, and irradiation, decay and counting times). The influence of the matrix is typically negligible. Most matrices appear to be transparent, because the atoms of which most of them are composed (H, C, O, N, P, and Si) hardly form any radioactive isotopes. This makes the method sensitive for measuring trace elements. The sensitivity obtained by neutron activation analysis could also be a function of nuclear parameters of the element in question (neutron cross section, isotope abundance, half-life, and gamma-ray abundance), available flux, length of

9880

irradiation, detector efficiency, matrix composition, and therefore the total sample size. It's self-validating: two or more analytical lines could also be used for the determination of an equivalent element allowing a crosscheck of the method. Some environmentally important elements, e.g., Cd, Cu, Ni and Pb can't be determined, a minimum of not at low concentrations. The technique is quite time-consuming.It takes about 2-4 weeks to urge information about elements involving radionuclides with long half-lives. NAA only gives the knowledge on the whole element concentrations. Information on compound structure and physical state cannot be immediately acquired. Less widely applied than other analytical techniques thanks to necessity of getting access to a reactor.

3] Thermal neutron activation analysis (TNAA)

NAA is typically called thermal NAA (TNAA) to worry that thermal neutrons play the foremost role within the activation process. quite 70 natural elements can induce radionuclides by means of (n,) reactions. the most advantages of the TNAA are: high-activation cross sections and no interfering reactions exist. the most drawback is that the perturbation of thermal flux by highly absorbing samples.[19]

4] Epithermal neutron activation analysis (ENAA)

Mainly non-thermal neutrons are wont to improve detection limits and precision of element determination like U, Tl, In, Au, Ta, Ag, Br, Co, I and Sb. ENAA is mainly applied when elemental content can be determined via a nuclide with high ratio of resonance activation integral (I0) to thermal neutron cross section (0): I0/0. To decrease the activity of nuclides where the ratio of resonance activation integral to thermal neutron cross section is low, thermal neutron filters of cadmium or boron are used. Therefore, this method is particularly useful for geological samples because many interfering nuclides (i.e., 24Na, 38Cl 42K, 46Sc, 51Cr, 59Fe) have low I0/0 ratios.[20, 21]ENAA is also very often to determine Br and I in biological samples.[22, 23]

5]Fast neutron activation analysis (FNAA)

Also called 14 MeV neutron activation analysis, it utilizes not only nuclear research reactor fast neutrons, but also fast neutrons produced by a neutron generator or by an isotopic neutron source.[2, 24]The 14 MeV neutrons are produced by the reaction between deuterium and tritium nuclei in the neutron Generators. They are produced by creating deuterium ions and accelerating these ions into adeuterium or tritium target.The D-D reaction is employed only in special circumstances because the neutron yield from the D-T reaction is 100 times higher.[25]In isotopic neutron sources the foremost common source of neutrons is that the spontaneous fission of californium-252 (252Cf). The average energy of neutrons from 252Cf is 2.3 MeV.[26]Neutrons may also be produced by a reaction between α particles and low Z elements (the most common element is Be). The α particle is emitted during radioactive decay of 238Pu, 226Ra or 241Am. Isotopic neutron sources although having an extended useful life and producing a comparatively constant flux of neutrons, have several disadvantages including the very fact they can't be close up when not in use. Isotopic neutron sources can't be added and therefore the energy spectrum of the emitted neutrons is broad and peaks at energies below the edge for a few important reactions.[27] One of the benefits of the FNAA lies within the incontrovertible fact that the utilization of fast neutrons froma neutron generator enables to perform field measurements, e.g., detections of metal contamination in soil.[28]The most important application of FNAA is that the analysis of oxygen content during an enormous sort of matrices including metals, geologic materials, coal, liquid fuels, ceramic materials, petroleum derivatives and fractions and chemical reaction products.[22, 26, 29]The determination of nitrogen in biological materials, including nitrogen as a measure of protein content[30]as well as nitrogen determination in explosives, fertilizers, and polymers are also important applications.FNAA are routinely analysed by other elements include Ag, Al, Au, Si, P, F, Cu, Mg, Mn, Fe, Zn, As, and Sn. [31]

6] Other types of Neutron Activation Analysis

a) Cyclic neutron activation analysis (CNAA)

Cyclic neutron activation analysis is based on repetitive short irradiation and measurement cycles, whereby the measurements are added. CNAA is used for the measurements of the concentrations of very short-lived isotopes of half-life <10sto improve their detection limits. However, it is limited by the transfer times of the sample from the irradiation unit to the counting place. These times should be shorter in time than the half-life of the radioisotope of interest. [32,33,34]The method has been applied for the determination of, e.g., Au, Ag, Cl, F, Hf, Sc, Se in biological samples. [13,2,35]
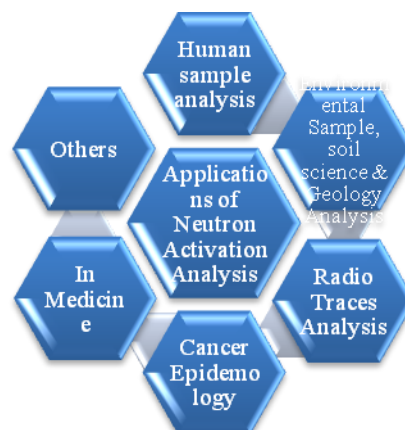
b) In vivo neutron activation analysis (IVNAA)

In vivo neutron activation analysis which is awell-established technique used for measure the main elements like C, Ca, K, N, O and P, or chemical element content within the human body.[36,37,38,39, 40]However, the elemental principles include that the body is exposed to neutron from either a neutron generator, isotopic neutron source, or a reactor. IVNAA allows reliable and reproducible reconstruction of molecular level components like total body fat, protein and minerals.

c) Prompt gamma neutron activation analysis (PGNAA)

Prompt gamma neutron activation analysis as mentioned in the first paragraph, is based on the measurement of rays emitted during nuclear reactions rather than gamma-rays emitted from radioactive decay. PGNAA is employed for the determination of low Z elements like B, H, N, P, S, and Si in various sorts of samples (geological samples, biological samples, and alloys).[41, 42, 43, 44]These elements are unusually determined by typical neutron activation analysis or detected with low sensitivity. However, PGNAA has also been applied for heavier elements, e.g., uranium.[45]Additionally,PGAA is also valuable for elements with large capture cross section and high gamma-ray yield, especially cadmium, samarium, and gadolinium.[46]

APPLICATIONS OF NEUTRON ACTIVATION ANALYSIS:

Fig4- Applications of neutron Activation Analysis

1) Human sample analysis:

Human samples analysed by neutron activation analysis are often divided into hard tissue, soft tissue and body fluids. In the case of bones usually Ca and P are determined to estimate the bone strength. (47, 48, 49, 50, 51, 52)For example, Tzaphlidou et al. 70 took rib bones at post-mortem, cleaned them of soft tissue and blood and analysed them with the help of NAA. It was found that the Ca/P ratio is more reliable for diagnosis of bone disorders than the individual concentrations of Ca and P.[50, 51, 52]Hard tissue, which is widely analysed by means of NAA, is hair. For assessing human environmental and occupational exposure, the hair analysis is most frequently used.[53, 54, 55, 56]

2) Environmental samples:

Air samples play a dominant role in environmental studies. The analysis of elemental concentrations in samples like aerosols, ash and particulate are used for assessing pollution.[57, 58, 59, 60, 61, 62, 63, 64, 65]In the case of aerosol analysis an interesting application is that the one proposed by Probst and associates.[60, 61]They determined gold, calcium and platinum concentration in aerosol samples without application of sample digestion. NAA of Pt using the 199Au daughter of 199Pt was performed. This analysis was affected by Au and Ca concentrations, but both interferences on Pt determination were corrected by applying suitable calculations. Platinum concentrations in air were the very best ever published for environmental investigations. The estimation of potential toxicity of ashes emitted by various kinds of incinerators was

the aim of another study. Extractable organ halogens (EOXs) were determined after extraction with toluene during a Soxhlet apparatus. EOX analysis suggested that ash samples contained many of organochlorine compounds. additionally, medical waste incinerator ashes were considered to possess relatively higher amount of organ iodine compounds than other ashes.[63,64,65,66]There also are other plants used as environmental pollution bio monitors, like cotton, white beet, or species typical for a given country area (e.g., Solanum lycocarpum in Brazil).[67, 68]

a. Soil Science:

Many agricultural processes and their consequences, like fertilization and herbicidal and pesticidal control, are influenced by surface and sub-surface movement, percolation and infiltration of water. Stable activatable tracers, like bromide, analyzed by NAA, have allowed the soil scientist to quantify the distribution of agricultural chemicals under a good sort of environmental and land use influences. In soil science, the utilization of bromide ion (Br-) in various forms (e.g., KBr, NaBr, SrBr2) was introduced as a non-reactive stable tracer in solute transport studies normally moving freely with the flux of water without substantial chemical or physical interactions with the soil. Typically, Br^- is extracted from soil and quantified using either a bromide selective electrode (sensitivity is ~10 mg/mL) or by high-performance liquid chromatography (sensitivity is ~0.010 mg/mL). Where the sensitivity is adequate, the selective conductivity method, which is straightforward, affordable and fast, is preferred. More recently, workers have reported that 20% of Br^- tracers, at low groundwater pH, could also be absorbed by iron oxides and kaolinite when present within the alluvial aquifer. We investigated the utilization of epithermal neutron activation analysis (ENAA) as a way of measuring Br^- directly in soil samples without an extraction. ENAA was chosen due to its high theoretical advantage factor over aluminium (i.e.,20), the principal interfering soil constituent, calculated for the 79Br (n,g) 80Br reaction compared to 27Al (n, g)28Al. Br^- was

measured (sensitivity is ~0.050 mg/g) in one gram soil samples from a five-second irradiation (fth = 2.5 x 1012 n/cm2/sec) employing a BN capsule [69]

b. Neutron Activation in Geology:

NDNAA and Compton-suppressed NAA are efficiently used for analysis of geological samples (i)for uranium content measurement in phosphate rocks and surrounding geology and (ii) in trace elemental analysis of rock samples. Trace elemental analysis of rock samples is especially important because these rocks can find a completely unique use as the coarse aggregate in sorts of concrete which will be developed for shielding of accelerator and reactor facilities. [70]

Precise determination of the basic content of the phosphate rocks is crucial within the understanding of geochemistry of the formation. INAA and delayed neutron activation analysis (DNAA) were employed to work out the concentration of uranium in some Egyptian environmental samples (Toshki soil, Aswan iron ore) and phosphate samples within the Red Sea coast area.[71]

Instrumental neutron activation analysis wants to detect and determine the basic composition of some beach rock samples within the South East Coast of Tamil Nadu, India. alongside other constituents, concentrations of the rare-earth element elements (REE) were measured. The authors used single comparator method during this study. They determined the fraction of 19 elements within the 15 samples collected from the world. High-resolution gamma spectrometry was used for the aim. Irradiated Standard Reference Material (SRM 1646aEstuarine sediment) was measured for calibration. The geochemical behaviour of REE in beach rock was studied.[72, 73]

The concentration of Se, V, As, Hg and Cd within the water from thermal springs were measured using NAA. The study was carried out to know the effect of thermal springs within the eastern Aegean in Greece, Ikaria, on beverage from sources near and much from the spring. The measured concentration of the weather didn't show statistically significant variation from that thanks to natural background.[74]

9876

Quantification was done on the concentrations of selenium, arsenic and 13 other elements in soil samples rich in selenium from the state of Punjab, India. The samples were irradiated in research reactor, and therefore the activated samples were counted using high-resolution γ ray spectrometry. Quantification was done using the comparator method using soil samples collected from a non-seleniferous region.[75]

3) Radio Traces Analysis:

a.Study the Redistribution of Uranium and Thorium due to Ore Processing

In the ten years between 1948 and 1958 ore mining within the us expanded from a cumulative total of 38,000 tons to 5.2 million tons involving more than 400 mines. Ores from these mines were chemically processed at an estimated 50 to 100 sites. These activities have resulted within the contamination of many square miles of surface and subsurface soils, and their corresponding ground waters, with uranium-238, thorium-232 and their radioactive daughters. In most cases these sites have various radioactive material materials like ore tailings, processing residues and leachates mixed with soil and usually covered with an uncontaminated soil layer several feet in thickness. In other cases, the tailings or wastes have remained exposed and hence are further distributed by wind and erosion. EBNAA has been developed as a strategy suitable for automation by which contaminated ore-processing sites are often characterized and their restoration monitored. [69]

b. The Use of Radiotracers to review the Fate of Hazardous Elements in Waste Material/Coal-Char Admixtures under Gasification- an Emerging Waste Management Technology

With an increasing emphasis being placed on the clean-up of hazardous waste sites from past technological operations, science has had to return up with ideas on the way to simultaneously decompose and stabilize a spread of mixed wastes which include radioactive materials. the foremost difficult of all wastes to clean-up is mixed waste. These may contain organic materials (dichlorobenzene, naphthalene, etc) alongside hazardous elements (cadmium, mercury, plutonium, thorium, uranium and other transuranic). Current waste destruction technology relies on oxidation of the waste (incineration); an alternate is that the storage of this waste. Both have drawbacks. Incineration requires high temperatures and therefore the resulting high fuel costs and volatilization of some hazardous components. Storage costs are proportional to the quantity of space haunted by the waste and therefore the regulations surrounding the waste, therefore, future storage of some existing radioactive material is unacceptable without volume reduction and stabilization. A process developed at MU, ChemChar gasification, helps minimize these problems. ChemChar gasification employing a coal char (a triple reverse burn coal product which is extremely porous) acts as both a surface for chemical reactions and a sequestering agent of hazardous elements. Initially the method uses the char as an absorber of the waste stream which is mixed on a 2:1 weight ratio (char: waste). A flame front is established which moves opposite the direction of oxygen flow and within the flame front organics are decomposed and other species tend to be chemically reduced. The volatile organics are carried off and trapped later while the immobile metals, metalloids and a few non-metals are sequestered on the char for final disposal or other disposition. The gasification process also leads to volume reduction, partitioning of probably usable organic solvents and therefore the production of a gas that would be used as an energy source. the target of the MURR component of this project is to develop a procedure by which radiotracers are often wont to determine Fates of hazardous elements during gasification in support of the utilization of gasification as a way of decomposing, stabilizing and reducing the quantity of hazardous mixed wastes including radioactive wastes resulting from the nuclear weapons program. so far Fates of arsenic, strontium, cadmium, cesium, mercury, uranium, thorium, neptunium and protactinium, chlorine (as an organochloride) and phosphorus (as organophosphorus surrogates for military wastes) are studied

during this reducing atmosphere using MURR produced radiotracers.[69]

c.Selenium Distribution in Aquatic Species in Selenium-contaminated Fresh-water Impoundments

This work is being done in collaboration with both federal and state agencies. Fresh-water ecosystems in California are grossly contaminated with selenium as a results of irrigation run-off from heavily used agricultural areas. The effect has been observed throughout most of the organic phenomenon. the target of those studies is to gauge the extent of the contamination and evaluate methodologies which may be efficacious within the reduction of selenium in these ecosystems.[69]

d. In-situ Radiotracers for Dosage-Form Testing

Over the last several years there has been a growing interest within the use of in-situ radiotracers to check new pharmaceuticals and dosage forms being developed for commercial distribution. This work has been done in collaboration with several pharmaceutical companies and university research centres. The in-situ radiotracers are produced through carefully designed irradiations done at the MURR and utilized in laboratory, animal, and during a few cases, human experiments. These methodologies offer significant advantages within the evaluation of encapsulations, time release, clearance and therefore the distribution of the pharmaceutical in animal and human models. [69]

4) Cancer Epidemiology

a.Nutritional Epidemiology-Nutritional and Biochemical/Genetic Markers of Cancer

This project is being carried out in collaboration with the Harvard school of medicine stemming from the rather striking findings reported in JAMA (December, 1996) showing a big protective effect thanks to a 200 microgram/day supplement of selenium against cancers of the colon, lung and prostate. One specific aim of the project is to gauge the connection between selenium status and cancer of the colon and prostate within the Physicians= Health Study. As proposed, this is often a five-year study using

prospectively collected blood samples because the biologic monitor of selenium status. If fully funded, this is able to be the most important prospective case-control study so far of selenium status and incidence of prostatic adenocarcinoma. Over the five years 2470 prostatic adenocarcinoma cases and 850 carcinoma cases are anticipated.[69]

b.Nutritional Epidemiology --A Cohort Study of the connection Between Diet, Molecular Markers, and Cancer Risk: the Canadian Study of Diet, Lifestyle and Health

A pilot study to characterize the nail as a biologic monitor for the dietary intake for selenium in Canada has been undertaken to increase our work to the main Canadian provinces. Suspected selenium determinants like smoking, use of dietary supplements, age and gender are going to be statistically evaluated during a population of over 700 subjects. Results are going to be compared with our earlier study of a female population drawn from 11 states within the U.S. the target of this work is to expand the collaborative MURR nutritional epidemiology program, that has enjoyed good success within the U.S., to Canada. This pilot will function a basis for 2 grant applications which will be submitted to the National Cancer Institute of Canada and therefore the Canadian Research Council. The work is being wiped out collaboration with the school of drugs, University of Toronto.[69]

c. Nutritional Epidemiology --Thyroid Cancer Study

This study is being carried out in collaboration with the Northern California Cancer Centre, Stanford University and therefore the University of California, San Francisco. Asian women who have immigrated to the U.S. West Coast experience a significantly increased incidence of thyroid cancer which is hypothesized to be a consequence of their substantial change in diet. Specifically, iodine intake is substantially increased and should stress a hypersensitive thyroid a condition observed in many of those subjects presumably thanks to chronically low iodine intakes before immigration. MURR is liable for two specific aims: characterizing the nail as a biologic

9878

monitor for iodine; and to live iodine in nails obtained during a nested case-control study of thyroid cancer. In these subjects, the utilization of iodine-containing contrast agents can confound analytical interpretations of any biologic monitor. From our work we've found that biologic monitors from subjects exposed to iodine-containing contrast agents are going to be influenced by the exposure for over a year. Consequently, these subjects should be screened out of nested case-control studies having an iodine hypothesis. The case-control comparison is blinded to our laboratory and can be evaluated beginning in 1999.[69]

d. Nutritional Epidemiology --Non-Melanoma carcinoma Study

This study was held in collaboration with Dartmouth school of medicine. there's some evidence that above normal intakes of arsenic may increase the danger of non-melanoma carcinoma. This hypothesis is being studied during a New Hampshire population routinely ingesting comparatively high levels of arsenic in their beverage supplies which are typically wells serving one residence or simply a couple of residences. we've shown that the arsenic concentration in nails is directly correlated with drinking-water arsenic levels. An NAA procedure to live arsenic in nails has been developed and applied during this nested pseudo-prospective case control study. Over 1000 samples are analysed over the last 2 years which is approximately the midpoint of the project. The case-control status will remain blind to our laboratory until the project is concluded. [69]

e. Nutritional Epidemiology-Molecular Epidemiology of prostatic adenocarcinoma

During this study, being conducted together with Johns Hopkins University, School of Hygiene and Public Health, we are investigating the connection of dietary and occupational exposures to selenium, cadmium and zinc and therefore the incidence of prostatic adenocarcinoma. this is often the foremost extensive study so far during which we've the chance to match two biologic monitors, nails and blood sera or plasma, during a nested case-control study having a selected disease outcome. Knock-Out Gene

Mouse Model for CF Mineral characterization studies with the knockout gene (CF) mouse model are wiped out collaboration with the MU Department of Veterinary life science. Bone and tooth mineralization differences between CF and normal mice were studied using NAA to live Ca, Mg, P, Na, K, F, Cl, Br and Mn. NAA was also wont to measure mineralization differences within the whole-body of the CF and normal mouse.[69]

5) NAA in Medicine:

Trace elements have important pertaining to the physiological and biochemical processes, and relative abundance and balance of various elements in trace quantities strongly influence the occurrence and advancement of the many diseases. Estimation of chemical element concentration in carcinoma, colorectal cancer, dysfunction and malignancy of thyroid has been done using neutron activation followed by high-resolution gamma spectrometric studies. NAA is one among the well-liked choices for trace-and ultra-trace-level quantitative estimation because it may be a highly accurate, precise and reproducible method even for measurements to the ppm and ppb level.Concentration of Ca, Cu, Co, I, Mg, Se, Fe, Zn, Hg, Ba and Cr at the trace level within the malignant tissues of colorectal cancer decided through NAA. The study was carried out for patients from Mexican population. The results were compared with those obtained for normal tissues within the same population. it had been observed that the quantity of Co, Fe, I and Ba changes due to incidence of colorectal cancer.[76]INAA want to detect and measure the arsenic content within the toenail of the carcinoma patients. Tissues from both basal skin carcinoma (BCS) and epithelial cell carcinoma (SCC) were examined from the patients of non-melanoma carcinoma.[77]Studies on the changes in chemical element concentration within the cancerous human prostate. they need used INAA to live the concentration of 43 trace elements and compared the results for malignant, benign hypertrophic and normal prostate. Of the 43 elements measured, concentration of 33 elements within the malignant prostate is above that within the benign hypertrophic tissue. For the weather

9879

Co, Hg, Rb, Sc, Se and Zn, a reverse trend was observed. in comparison with the traditional tissue, lower contents of Sc, Se, Zn, Rb and Cd were detected within the malignant prostate.[78]

Neutron activation analysis through monitoring of the delayed gamma ray (DGNA) together with dual-energy X-ray absorption was employed by to estimate the entire body calcium.[79]Gamma ray imaging plays a big role within the pharmaceutical industry in development and progress of a drug delivery system. the quality sort of radiolabelling of the drug molecules is completed using a number of the foremost commonly used medically important radioisotopes, like ^{99m}Tc or^{111}In. except for complex drug molecules, radiolabel is produced through in place neutron activation.[80]NSECT or neutron-stimulated emission computerized tomography is one among the foremost advanced imaging techniques employed to review the isotope distribution in biological tissue. the tactic depends on irradiation of the sample by fast neutrons. The gamma rays emitted within the natural process induced within the isotopes within the tissue under study are monitored to construct tomographic images of every section of the sample. Though the instrumentation is dear, high sensitivity of the technique has rendered it suitable to be used for cancer staging, detection of carcinoma.[81,82,83]

6) Other applications:

a. Calcium Metabolism Study

In support of the MU Department of kid Health, the study of calcium absorption in pig and lamb models using Ca-47 produced and processed at the MURR from an enriched Ca-46 target was administered. In support of human studies with low birth-weight infants, juvenile atrophic arthritis and cystic fibroticsa dual-enriched-isotope methodology, supported stable isotopes measured via NAA, has been developed to live true absorption of calcium from experimental diets.[69]

b. Semiconductor materials and other high-purity materials

Neutron Activation Analysis (NAA) is employed to live trace and ultra trace-element concentrations of impurities and/or dopants in semiconductors and other high-purity materials. The behaviour of semiconductor devices is strongly influenced by the presence of impurity elements either added intentionally (doping with B, P, As, Au, etc.) or contaminants remained during incomplete purification of the semiconductor material during the manufacture of devices. Small quantities of impurities of concentrations below 1 ppb can show a big effect on the standard of semiconductor devices. the target of the client is to demonstrate that a chemical or material meets or exceeds purity requirements required by the top user. In some instances, the MURR Nuclear Analysis Group conducts a multi-element qualitative and quantitative chemical analysis which then is employed because the certificate of study for that substance. In other cases, the NAA staff work with clients to determine purification factors at various stages within the production process of high-purity materials like silicon or, the efficacy of cleaning and leaching procedures. In still other cases we are ask to demonstrate that a selected impurity or set of impurities is below the extent of technical or regulatory concern. NAA is that the elemental analysis method of choice for these projects due to the limited sample handling required and therefore the high sensitivity for several elements of interest.[69]

c. Sedimentation Technique of powder:

The determination of particle sizes by sedimentation techniques has been facilitated by activation. The powder to be measured is rendered radioactive, then dispersed during a viscous liquid and allowed to settle. the number of fabrics during a particular layer after settling is rapidly determined by measurement of the radioactivity within the layer.[84, 85,86]

d. Application in Mines:

Remote analysis by activation is that the direct logging of oil wells and other geological drillings. it's been found practically to lower small radioisotope neutron sources or neutron generating tubes into such holes. the discharge of either prompt or delayed photons from the irradiated surrounding media

provides considerable information concerning the stratigraphy encountered within the drilling. Of course, drill cores delivered to the surface can also be analysed by activation techniques.[87,88, 89]

e. Identification in crime suspect:
Residues from the primer can often be found on the hands of an individual who has recently fired a gun. Activation analysis want to detect minute traces of antimony and barium. during this later work the hand is wiped with paper, moistened with 1% aqua fortis and therefore the paper is irradiated for one hour during a reactor. The activated antimony and barium are isolated by a radiochemical separation and quantitatively determined by gamma spectrometry. The technique is capable of giving a solution during a few hours.[90, 91]

f. NAA application to detect criminality:
High speed photographic technique was studied insuch a way where residues are deposited on the hand. Furthermore, an activation method was developed for the determination of the distribution of residues on the hand. A collodion film was applied to the rear of the thumb, web and fore- finger of the firing hand. After allowing the film to dry it had been stripped off then irradiated for 24 hours during a flux of 2 x 10^{12} neutrons/sec/sq. cm. The activity, mainly Na^{24}, was allowed to decay for four days then the collodion was placed in touch with X-ray film and an autoradiograph produced. The black spots indicate the position of radioactive spots on the collodion cast, these were cut out for identification and measurement by gamma spectrometry. this system detected residues on the hand after a gun had been fired in about 90%of the tests.[92]

g. Growth of mosses was determined by NAA:
Mosses have a comparatively long history of use as biomonitors, research on the uptake and localization of elements and on their sources they're recently neglected. Utility of mosses as biomonitoring tools to work out the basic pollution levels within the air of MAVT as measured by INAA. In remote and barren areas, the basic composition of unwashed

moss is suffering from entrapped crustal materials. the very best pollution levels were found in samples from Tollocan, Alameda, Reforma, and Santın (UR) and San Miguel (TR), which are all located in urban regions. The presence of high pollution levels in samples are often attributed to proximity of commercial areas that include an outsized number of vehicles, wind dynamics, and anthropogenic activities that contribute to the degradation of air quality.[93]

CONCLUSION:
The Neutron activation analysis is one of the preferred method for quantitative analysis of various types of samples and has thus found wide variety of application. It is a highly accurate method and can reliably be applied for the measurement of concentration of elements at the trace and ultra trace level. The examples illustrated in applications can be a useful tool in the scientific studies. Hence, NAA is emphasised as an only a tool and vital to use the technique for gathering background information to allow a meaningful interpretation of analytical data.

Conflict of interest: There was no conflict of interest in this study.

REFERENCES:

1. Greenberg, R.R., Bode P, De Nadai Fernandes EA (2011) Neutron activation analysis: a primary method of measurement. Spectrochimica Acta Part B, 66 issues 3-4; 2011, p193-241.
2. Bode, P., and J. J. M. De Goeij. "Encyclopedia of environmental analysis and remediation." (1998): 2-8.
3. Hamidatou L, Slamene H, Akhal T, Zouranen B. Concepts, instrumentation and techniques of neutron activation analysis. Imaging and Radioanalytical Techniques in Interdisciplinary Research Fundamentals and Cutting-Edge Applications, InTech, Rijeka. 2013 Mar 13:141-78.
4. Guinn VP. A short history of nuclear activation analysis. InNuclear Analytical Methods in the Life Sciences 1990 (pp. 1-7). Humana Press, Totowa, NJ.

9881

5. Cristache C, Duliu OG, Ricman C, Toma M, Dragolici F, Bragea M, Done LA. Determination of elemental content in geological samples. Rom. Journ. Phys. 2008 Jan 1;53(7-8):941.

6. Seal MS, Mills WA, Terrill Jr JG. Neutron activation analysis. Public Health Reports. 1957 Apr;72(4):329.

7. Kreft I, Stibilj V, Trkov Z. Iodine and selenium contents in pumpkin (Cucurbita pepo L.) oil and oil-cake. European Food Research and Technology. 2002 Oct;215(4):279-81.

8. Hentig R, Goldbrunner T, Feilitzsch F, Angloher G. Fresenius J. of Anal. Chem. 1998;360:664nucx.

9. Wildhagen D, Krivan V. Multi-element characterization of high-purity titanium dioxide by neutron activation analysis. Fresenius' journal of analytical chemistry. 1997 Sep;359(3):230-8.

10. White MA, Sabbioni E. Trace element reference values in tissues from inhabitants of the European Union. X. A study of 13 elements in blood and urine of a United Kingdom population. Science of the Total Environment. 1998 May 27;216(3):253-70.

11. Cao L, Tian W, Ni B, Wang P, Zhang Y. Radiochemical neutron-activation analysis of uncertified ultra-trace rare earth elements in two biological certified reference materials. Analytical and bioanalytical chemistry. 2002 Jan;372(2):397-400.

12. K. Shinotsua, M. Ebihara, Anal. Chim. Acta, 338 (1997) 237

13. Rietz B, Krarup-Hansen A, Rorth M. Determination of platinum by radiochemical neutron activation analysis in neural tissues from rats, monkeys and patients treated with cisplatin. Analytica chimica acta. 2001 Jan 1;426(1):119-26.

14. Polkowska-Motrenko H, Danko B. R. Dybczyn ski, A. Koster-Ammerlaan, P. Bode. Anal. Chim. Acta. 2000;408:89.

15. Orvini E, Speziali M. Applicability and limits of instrumental neutron activation analysis: State of the art in the year 2000. Microchemical journal. 1998 May 1;59(1):160-72.

16. Weise HP, Görner W, Hedrich M. Determination of elements by nuclear analytical methods. Fresenius' journal of analytical chemistry. 2001 Jan;369(1):8-14.

17. Tian W, Ni B, Wang P, Cao L, Zhang Y. Metrological role of neutron activation analysis. IB. Inherent characteristics of relative INAA as a primary ratio method of measurement. Accreditation and quality assurance. 2002 Jan;7(1):7-12.

18. M. H. Gerzabek, G. Haberhauer, A. Krenn, T. Shinonaga, Use of nuclear techniques in environmental and pollution studies, in: Proc. Symp. on Nuclear Techniques in Integrated Plant Nutrient, Water and Soil Management, Vienna, Austria, IAEA, Vienna, 2000.

19. Csikai J, Király B, Sanami T, Michikawa T. Studies on thermal neutron perturbation factor needed for bulk sample activation analysis. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2002 Aug 11;488(3):634-41.

20. Capote Rodriguez G, Rivero A, Bermudez J, Guevara S, Arribére M, Insfrán J, Zayas G. Determination of selenium in nickel and cobalt concentrates applying epithermal neutron activation analysis. Journal of radioanalytical and nuclear chemistry. 1997 Sep 17;223(1-2):217-20.

21. Landsberger S, Peshev S, Becker DA. Determination of silicon in biological and botanical reference materials by epithermal INAA and Compton suppression. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 1994 Dec 30;353(1-3):601-5.

22. Hou X, Chai C, Qian Q, Li C, Wang K. Determination of bromine and

iodine in biological and environmental materials using epithermal neutron activation analysis. Fresenius' journal of analytical chemistry. 1997 Apr;357(8):1106-10.

23. Yonezawa C, Matsue H, Yukawa M. Non-destructive determination of trace amounts of iodine in biological samples by epithermal neutron activation and Compton suppression gamma-ray spectrometry. Journal of radioanalytical and nuclear chemistry. 2003 Jan 17;255(1):105-9.

24. James WD. 14 MeV fast neutron activation analysis in the year 2000. Journal of Radioanalytical and Nuclear Chemistry. 2000 Jan;243(1):119-23.

25. Senhou A, El Khoukhi T, Chouak A, Cherkaoui RE, El Yahiaoui A, Lferde M. Study of the accumulation of air pollution by the biological indicators, using 14 MeV neutron activation. Radiation Physics and Chemistry. 2001 Jun 1;61(3-6):701-3.

26. Morgan WD, Vartsky D, Ellis KJ, Cohn SH. A comparison of 252Cf and 238Pu, Be neutron sources for partial-body in vivo activation analysis. Physics in Medicine & Biology. 1981 May;26(3):413.

27. B. J. Hughey, Nucl. Instr. Meth. Phys. Res., B95 (1995) 393

28. James WD. Fast neutron activation analysis at Texas A&M University. Journal of radioanalytical and nuclear chemistry. 1997 May;219(2):187-90.

29. Owrang F, Mattsson H, Olsson J, Pedersen J. Investigation of oxidation of a mineral and a synthetic engine oil. Thermochimica Acta. 2004 Apr 8;413(1-2):241-8.

30. C . A . A d e s a n m i , A. A. Essiett, F. A.Balogun, Nucl. Instr.Meth. Phys. Res., A505 (2003) 521

31. Verri G, Mezzetti F, Da Re A, Rapezzi L, Gribkov V. Fast Neutron Activation Analysis of gold by inelastic scattering, 197Au (n, n'gamma) 197Aum, by means of

Plasma Focus device. Nukleonika. 2000;45(3):189-91.

32. E. Witkowska, K. Szczepaniak, M. Biziuk. Some applications of neutron activation analysis: A review. Journal of Radioanalytical and Nuclear Chemistry, Vol. 265, No. 1 (2005) 141-150

33. Khamis I, Othman I, Nasri M, Bakkour M. Transfer time optimization of a rapid cyclic instrumental neutron activation analysis for trace element detection. Review of Scientific Instruments. 2001 Feb;72(2):1492-4.

34. Çetiner MA, Demirel H, Demirbaş A, Yücel H, Celenk I. Automation of a pneumatic system by controlling a microcomputer equipped with a custom add on board for neutron activation analysis. Applied radiation and isotopes. 1997 Mar 1;48(3):397-402.

35. Cheng TP, Morris JS, Koirtyohann SR, Spate VL, Baskett CK. The analysis of human nails for 24 elements via k0 and cyclic neutron activation analysis. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 1994 Dec 30;353(1-3):457-60.

36. Arnold ML, McNeill FE, Prestwich WV, Chettle DR. System design for in vivo neutron activation analysis measurements of manganese in the human brain: based on Monte Carlo modeling. Applied Radiation and Isotopes. 2000 Nov 15;53(4-5):651-6.

37. Arunabh S, Feuerman M, Ma R, Aloia JF. Total body phosphorus in healthy women and ethnic variations. Metabolism-Clinical and Experimental. 2002 Feb 1;51(2):180-3.

38. O'Meara JM, Blackburn BW, Chichester DL, Gierga DP, Yanch JC. The feasibility of accelerator-based in vivo neutron activation analysis of nitrogen. Applied Radiation and Isotopes. 2001 Nov 1;55(6):767-74.

39. Pietrobelli A, Heymsfield SB. Establishing body composition in obesity. Journal of endocrinological investigation. 2002 Nov;25(10):884-92.

40. Prestwich WV, McNeill FE. Lithium target performance evaluation for low-energy accelerator-based in vivo measurements using gamma spectroscopy. Applied Radiation and Isotopes. 2003 Mar 1;58(3):321-31.

41. Borsaru M, Berry M, Biggs M, Rojc A. In situ determination of sulphur in coal seams and overburden rock by PGNAA. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2004 Jan 1;213:530-4.

42. Naqvi AA. Prompt gamma ray analysis of Portland cement sample using keV neutrons with a Maxwellian energy spectrum—a Monte Carlo study. Radiation Physics and Chemistry. 2003 Aug 1;67(6):695-701.

43. Nunes WV, Da Silva AX, Crispim VR, Schirru R. Explosives detection using prompt-gamma neutron activation and neural networks. Applied radiation and isotopes. 2002 Jun 1;56(6):937-43.

44. Nair AG, Acharya R, Sudarshan K, Gangotra S, Reddy AV, Manohar SB, Goswami A. Development of an internal monostandard instrumental neutron activation analysis method based on in situ detection efficiency for analysis of large and nonstandard geometry samples. Analytical chemistry. 2003 Sep 15;75(18):4868-74.

45. Molnár G, Révay ZS, Veres Á, Simonits A, Rausch H. Cold neutron facility for prompt gamma-neutron activation analysis. Journal of radioanalytical and nuclear chemistry. 1993 Jan;167(1):133-7.

46. Lindstrom RM. Reference material certification by prompt-gamma activation analysis. Fresenius' journal of analytical chemistry. 1998 Feb;360(3):322-4.

47. Dilmanian FA, Weber DA, Yasumura S, Kamen Y, Lidofsky L, Heymsfield SB, Pierson RN, Wang J, Kehayias JJ, Ellis KJ. Performance of the delayed- and prompt-gamma neutron activation systems at Brookhaven National Laboratory. In vivo body composition studies 1990 (pp. 309-315). Springer, Boston, MA.

48. Cohn SH, Shukla KK, Dombrowski CS, Fairchild RG. Design and calibration of a "broad-beam" 238Pu, Be neutron source for total-body neutron activation analysis. Journal of nuclear medicine. 1972 Jul 1;13(7):487-92.

49. Economos CD, Nelson ME, Singh MF, Kehayias JJ, Dallal GE, Heymsfield SB, Wang J, Yasumura S, Ma R, Pierson Jr RN. Bone mineral measurements: a comparison of delayed gamma neutron activation, dual-energy x-ray absorptiometry and direct chemical analysis. Osteoporosis international. 1999 Sep;10(3):200-6.

50. Zaichick V, Tzaphlidou M. Determination of calcium, phosphorus, and the calcium/phosphorus ratio in cortical bone from the human femoral neck by neutron activation analysis. Applied Radiation and Isotopes. 2002 Jun 1;56(6):781-6.

51. Zaichick V, Tzaphlidou M. Calcium and phosphorus concentrations and the calcium/phosphorus ratio in trabecular bone from the femoral neck of healthy humans as determined by neutron activation analysis. Applied radiation and isotopes. 2003 Jun 1;58(6):623-7.

52. Tzaphlidou M, Zaichick V. Neutron activation analysis of calcium/phosphorus ratio in rib bone of healthy humans. Applied Radiation and Isotopes. 2002 Dec 1;57(6):779-83.

53. Kupera J, Bencko V, Tejral J, Borska L, Soukal L, Randa Z. Biomonitoring of occupational exposure: Neutron activation determination of selected metals in the body tissues and fluids

of workers manufacturing stainless steel vessels. Journal of radioanalytical and nuclear chemistry. 2004 Jan 17;259(1):7-11.

54. Alekseeva OA, Belov AG, Frontasyeva MV, Gundorina SF, Gustova MV, Kusmenko LG, Perelygin VP, Zaverioukha OS. Neutron, gamma and Roentgen fluorescent activation analysis of hair of children suffering from bronchial asthma. Radiation measurements. 2001 Jun 1;34(1-6):521-5.

55. Ramakrishna VV, Singh V, Garg AN. Occupational exposure amongst locomotive shed workers and welders using neutron activation analysis of scalp hair. Science of the total environment. 1996 Dec 9;192(3):259-67.

56. Man CK, Zheng YH, Mak PK. Hair analysis of spastic children in Hong Kong. Science of the total environment. 1996 Nov 22;191(3):291-5.

57. J.P. Lodge Jr., Methods of Air Sampling and Analysis, Third Edition, Lewis Publishers, Inc., Chelsea, MI (1989).

58. Karakaş DU, Ölmez I, Tosun S, Tuncel G. Trace and major element compositions of Black Sea aerosol. Journal of radioanalytical and nuclear chemistry. 2004 Jan 17;259(1):187-92.

59. Baker AR, Thompson D, Campos ML, Parry SJ, Jickells TD. Iodine concentration and availability in atmospheric aerosol. Atmospheric Environment. 2000 Jul 26;34(25):4331-6.

60. Khodzher TV, Obolkin VA, Potemkin VL, Bufetov NS, Tomza U, Rahn KA. A study of trace elements in atmospheric aerosols of the Eastern Siberia using neutron activation and synchrotron radiation X-ray fluorescence analysis. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2000 Jun 21;448(1-2):413-8.

61. Probst TU, Rietz B, Alfassi ZB. Platinum concentrations in Danish air samples determined by instrumental neutron activation analysis. Journal of Environmental Monitoring. 2001;3(2):217-9.

62. Alfassi ZB, Probst TU, Rietz B. Platinum determination by instrumental neutron activation analysis with special reference to the spectral interference of Sc-47 on the platinum indicator nuclide Au-199. Analytica chimica acta. 1998 Mar 10;360(1-3):243-52.

63. Loganathan BG, Kannan K, Watanabe I, Kawano M, Irvine K, Kumar S, Sikka HC. Isomer-specificdetermination and toxic evaluation of polychlorinated biphenyls, polychlorinated/brominated dibenzo-p-dioxins and dibenzofurans, polybrominated biphenyl ethers, and extractable organic halogen in carp from the Buffalo River, New York. Environmental science & technology. 1995 Jul 1;29(7):1832-8.

64. Kawano M, Ueda M, Matsui M, Kashima Y, Matsuda M, Wakimoto T. Extractable organic halogens (EOX: Cl, Br and I), polychlorinated naphthalenes and polychlorinated dibenzo-p-dioxins and dibenzofurans in ashes from incinerators located in Japan. Organohalogen Compounds. 1998; 36:221-4.

65. Kannan K, Kawano M, Kashima Y, Matsui M, Giesy JP. Extractable organohalogens (EOX) in sediment and biota collected at an estuarine marsh near a former chloralkali facility. Environmental science & technology. 1999 Apr 1;33(7):1004-8.

66. Matsui M, Kashima Y, Kawano M, Matsuda M, Ambe K, Wakimoto T, Doi R. Dioxin-like potencies and extractable organohalogens (EOX) in medical, municipal and domestic waste incinerator ashes in Japan.

Chemosphere. 2003 Dec 1;53(8):971-80.

67. França EJ, Fernandes EA, Bacchi MA, Tagliaferro FS. Pathway of rare-earth elements in a Brazilian forestry fragment. Journal of alloys and compounds. 2002 Oct 7;344(1-2):21-6.

68. Maria SP, Figueiredo AM, Ceccantini G. Determination of the contents and distribution characteristics of rare earth elements in Solanum lycocarpum from tropical ecosystems in Brazil by INAA. Journal of Radioanalytical and Nuclear Chemistry. 2000 May;244(2):303-6.

69. Glascock MD, Neff H. Neutron activation analysis and provenance research in archaeology. Measurement Science and Technology. 2003 Jul 29;14(9):1516.

70. Pai BHV et al. Estimation of trace element concentration and neutron induced radioactivity in rock samples of different geological compositions for neutron shielding. Indian Journal of Pure & Applied Physics. 2016; 54(01):7-14

71. El-Taher A. INAA and DNAA for uranium determination in geological samples from Egypt. Applied Radiation and Isotopes. 2010; 68(6):1189-1192.

72. Avisankar R, Eswaran P, Seshaderssan NP, Rao B. Instrumental neutron activation analysis of beach rock samples of South East Coast of Tamilnadu, India. Nuclear Science and Techniques. 2007; 18(4):204-211.

73. Ravisankar R, Manikandan E, Dheenathayalu M, Rao B, Seshadreesan NP, Nair KGM. Determination and distribution of rare earth elements in beach rock samples using instrumental neutron activation analysis (INAA). Nuclear instruments and methods in physics research section B: Beam interactions with materials and atoms. Nuclear Instruments and Methods in Physics Research B. 2006; 251(2):496-500.

74. Contis ET. Analysis of drinking water near and far from thermal springs using instrumental neutron activation analysis. Developments in Food Science. 1995; 37: 2109-2127.

75. Srivastava A, Bains GS, Acharya R, Reddy AVR. Study of seleniferous soils using instru-mental neutron activation analysis. Applied Radiation and Isotopes. 2011; 69(5):818-821.

76. Arriola H, Longoria L, Quintero A, Guzman D. INAA of trace elements in colorectal cancer patients. Biological Trace Element Research. 1999;71(Issue 1):563-568.

77. Rees JR, Zens MS, Gui J, Celaya MO, Riddle BL, Karagas MR. Non melanoma skin cancer and subsequent cancer risk. PloS one. 2014 Jun 17;9(6): e99674.

78. Zaichick V, Zaichick S. Trace element levels in prostate gland as carcinoma's markers. Journal of Cancer Therapy. 2017;8(02):131.

79. Aloia JF, Ma R, Vaswani A, Feuerman M. Total-Body Calcium Estimated by Delayed Gamma Neutron Activation Analysis and Dual-Energy X-ray Absorptiometry. Osteoporosis International. 1999;10(6):510-515

80. Davis SS, Hardy JG, Newman SP, Wilding IR. Gamma scintigraphy in the evaluation of pharmaceutical dosage forms. European Journal of Nuclear Medicine. 1992; 19(Issue 11):971-986

81. Kapadia AJ et al. Neutron stimulated emission computed tomography for diagnosis of breast cancer. IEEE Transactions on Nuclear Science. 2008;55(1):501-509

82. Viana RS, Valverde MG, Mekkaoui C, Yoriyaz H, Jackowski M. NSECT sinogram sampling optimization by normalized mutual information. Progress in Biomedical Optics and Imaging - Proceedings of SPIE. 2015;9412.

83. Nandy, Maitreyee. "Neutron Activation Analysis: Application in Geology and Medicine." (2018).

9886

84. Verri G, Mezzetti F, Da Re A, Rapezzi L, Gribkov V. Fast Neutron Activation Analysis of gold by inelastic scattering, 197Au (n, n'gamma) 197Aum, by means of Plasma Focus device. Nukleonika. 2000;45(3):189-91.,

85. Abraham BM, Flotow HE, Carlson RD. Particle size determination by radioactivation. Analytical Chemistry. 1957 Jul 1;29(7):1058-60.

86. Bate, L. C., Hampton, W., and Leddicotte, G. W., U. S. At. Energy Comm. Rept. Ornl-2866, 31 (1960)

87. Caldwell RL. Using nuclear methods in oil well logging. Nucleonics (US) Ceased publication. 1958 Dec 1;16.

88. Caldwell RL, Mills Jr WR. Activation analysis in petroleum exploration research. Nuclear Instruments and Methods. 1959 Nov 1;5(5):312-22.

89. Sayre EV. Methods and applications of activation analysis.

Annual review of nuclear science. 1963 Dec;13(1):145-62.

90. Harrison HC, Gilroy R. Firearms discharge residues. J. Forensic Sci. 1959 Apr;4(2):184-99.

91. Ruch RR, Buchanan JD, Guinn VP, Bellanca SC, Pinker RH. Neutron Activation Analysis in Scientific Crime Detection-Some Recent Developments. Journal of Forensic Sciences (US). 1964 Jan 1;9.

92. Coleman RF. The Application of Neutron Activation Analysis to Forensic Science. Atomic Weapons Research Establishment, Aldermaston, Eng.; 1967 Jan 1.

93. R. Mejia-Cuero, G. García- Rosales, L. C. Longoria-Gandara, M. C. Lopez-Reyes, and P. Avila-Perez. Application of Neutron Activation Analysis for Determination of As, Cr, Hg, and Se in Mosses in the Metropolitan Area of the Valley of Toluca, Mexico. Journal of Chemistry Volume 2015,1-13.