



Review on PIXE: Accelerator Based Analytical Technique

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Abstract: The application of different analytical techniques for trace elemental analysis has assumed a relevant role in all fields. In particular, in the last thirty years techniques that exploit instrumentation typical of nuclear physics have been developed for the analysis of samples from every conceivable field of scientific or technical interest.

Particle induced x-ray emission (PIXE) was first introduced at the Lund Institute of Technology in 1970 by Johansson et al. It is a powerful and relatively simple analytical technique that can be used to identify and quantify trace elements. PIXE serves as an excellent tool for trace element analysis because of its capability to detect simultaneously several elements present at very low concentrations. PIXE has rapidly gained acceptance as a valuable analytical tool, because of the ever-increasing need for elemental analysis of very small amounts of sample. Respected for its practical accuracy and detection range of parts per million, PIXE has enjoyed a secure place in the analytical arsenal of the nuclear physics laboratory. PIXE analysis consists of two parts. The first is to identify the atomic species in the target from the energies of the characteristic peaks in the X-ray emission spectrum and second part is to determine the quantity of the elements present in the target from the intensity of its characteristic X-ray emission spectrum.

Due to its high sensitivity and multi-elemental analysis capability, PIXE has found application in the trace elemental analysis of samples from almost every conceivable field of scientific or technical interest. Some of these fields are Biomedicine, Environment, Geology, Archaeology, Material science, Forensic studies and Industrial applications.

Index Terms - PIXE, Accelerator, Nuclear Analytical Techniques

I. INTRODUCTION

The foundation of analytical techniques for the identification of elements on the basis of X-ray emission analysis was laid way back in 1914 when Moseley first related the atomic number of an element with the frequency of the characteristic X-rays emitted by the element. This breakthrough heralded the development of wavelength dispersive X-ray spectrometry. Owing to its excellent sensitivity and unmatched resolution this analytical technique secured a dominant position in X-ray spectroscopy.

The early 1960's witnessed the prevalent use of X-ray emission spectrometers for elemental analysis. At present, a plethora of X-ray spectrometers are being exploited for extracting both qualitative and quantitative information from a specimen. With some of these spectrometers, sensitivities in the range of parts per million are attainable for most of the elements. Moreover, accuracies of the order of a few tenths of a percent are realizable with these spectrometers. The time of analysis on the order of minutes could be attained with scanning spectrometers and even less for multichannel instruments.

Among the most important features of X-ray spectroscopic technique are its non-destructive nature and ability to obtain measurable signals from as small as one milligram of a specimen. The availability of a wide range of well analyzed calibration standards coupled with the development of algorithms relating X-ray emission intensity with elemental composition has facilitated the application of this technique in diverse analytical disciplines. The step wise procedure involved in X-ray emission analysis can be enumerated as follows:

Step 1: Bombardment of the specimen with a high energy projectile (photons, electrons, protons etc.) and consequent emission

of characteristic radiation from the specimen.

Step 2: Identification of the characteristic emission line from the element of interest by using an energy or wavelength dispersive spectrometer.

Step 3: Measurement of characteristic emission line intensity via integration of the characteristic X-rays.

Step 4: Quantification of the element by conversion of the characteristic emission line intensity to elemental concentration by using a suitable calibration procedure.

Hence, all X-ray based spectrometers consist of an excitation source, a mechanism for separating and isolating characteristic emission lines and a tool for measuring the intensities of these lines. A dedicated computer for processing the obtained data and extracting the elemental composition may also be incorporated in state of the art and sophisticated spectrometers.

2 Basis of Qualitative and Quantitative X-ray Emission Analysis

2.1 Qualitative Analysis

Qualitative analysis of a sample is based on the identification of the characteristic emission lines (either one or more) emitted from all the elements present in the sample. The spectrometers resolving power, that is, its ability to separate the spectral lines and its operating range of wavelength decide how many of these characteristic emission lines can be measured. Most of the spectrometers operate over the range 0.2 to 20 Å and hence are able to identify majority of the K and L series lines. Additionally, a few M series lines from the elements with higher atomic number are also detected. This implies that practically all elements with $Z > 8$ can be identified with the number of lines varying from 2 to 3 per element for the low Z elements to 20 to 30 for the high Z ones. Qualitatively, it is enough to detect one or two lines for the positive identification of an element. This is done by using Moseley's law which relates the frequency ν of the emission line with the atomic number Z of the element

$$\nu = K(Z-\sigma)^2 \dots\dots\dots(1)$$

A simple equation relating wavelength λ to energy E of the X-ray photon is used for identifying the atomic species

$$E(keV) = \frac{1.24}{\lambda(nm)} \dots\dots\dots(2)$$

In practice, data tables relating either wavelength λ or energy E with atomic number Z are generally used for the qualitative identification of elements from their emission spectra. Usually most of the spectrometers

compromise on sensitivity at longer wavelengths and lose their ability to detect low Z ($Z < 12$) elements. Besides, the lower penetration of long wavelength X-rays in conjunction with the fact that they arise from molecular rather than atomic orbital transitions makes it practically very difficult to identify elements with $Z < 9$.

2.2 Quantitative Analysis

Quantitative analysis of a given element is based on measuring one selected emission line and relating the intensity of this line to concentration. This relationship turns out to be linear only for a very limited concentration range. In most cases, the intensity of the emitted line is determined by the so called “matrix effects”, that is, the effect of other elements present in the sample apart from the concentration of the excited element. By carefully calibrating and calculating, these matrix effects can be corrected. Sample homogeneity plays a crucial role in accurate quantification since the characteristic X-ray lines have a small penetration (typically 1-1000 μm).

X-ray emission spectrum can be analyzed for extracting the quantitative information depending on the mode of excitation. The four existing modes of excitation are:

- X-ray tube excitation
- Particle excitation (including protons, heavy charged particles and electrons)
- Radioisotope excitation
- Synchrotron radiation based excitation

In 1912 itself, two years before Moseley’s law came into picture, Chadwick showed that alpha particles (particles heavier than electrons) from a radioactive source can give rise to X-ray emission [1]. Nevertheless, it was soon realized that with such a low-intensity excitation source it was practically impossible to use radioisotopes for analytical purposes. Before the advent of accelerators, electron beams of several keV energies were used to excite the specimen under study in order to produce X-rays.

Even though the production cross-sections of X-rays for electron beams of several keV energies were found to be similar to those obtained with protons and helium ions of MeV energies, with the entry of particle accelerators into the analytical arena, excitation via electrons received a setback primarily because of much smaller background contribution from bremsstrahlung of protons or helium ions when compared to electrons. Anticipating this constraint with respect to electron beam, studies on the possibility of using heavy charged particles for analytical purposes with a prior knowledge of X-ray production cross-section as a function of particle energy and atomic number started during the 1960s. During the same period, a technological breakthrough in gamma ray and X-ray spectroscopy was made with the development of high resolution semiconductor detectors. These detectors enabled the resolution of X-ray emission lines from adjacent elements with $Z \geq 10$ and the simultaneous detection of up to 30 elements in the periodic table. The consequent period witnessed a rapid progress in the development of both the accelerators and solid state detectors thereby paving way for highly reliable atomic and nuclear physics based research.

3 Particle Induced X-ray Emission (PIXE)

Particle Induced X-ray Emission (PIXE) was first introduced by Johansson et al. [2] at the Lund Institute of Technology in 1970. It is a relatively simple analytical technique that can be used to identify and quantify trace elements. Several analytical techniques have been used for trace element analysis; however their sample preparation procedures are usually quite complicated and also have the disadvantage of long analysis time. Among the ion-beam analysis techniques, PIXE is one of the most powerful techniques for material analysis, since its sample preparation methodology is generally simple and it requires a short measuring time. PIXE serves as an excellent tool for trace element analysis because of its capability to detect simultaneously several elements present at very low concentrations. PIXE has rapidly gained acceptance as a valuable analytical tool, because of the ever-increasing need for elemental analysis of very small amounts of sample. Respected for its practical accuracy and detection range of parts per million, PIXE has enjoyed a secure place in the analytical arsenal of the nuclear physics laboratory. PIXE analysis consists of two parts. The first is to identify the atomic species in the target from the energies of the characteristic peaks in the X-ray emission spectrum and second part is to determine the quantity of the elements present in the target from the intensity of its characteristic X-ray emission spectrum. The history behind the development of this technique can be found in some review papers [3-5]. The technical improvisations made and the applications of PIXE in diverse fields were presented in different international conferences on PIXE and text books [4-11].

3.1 Principle Underlying PIXE

Particle Induced X-ray Emission is based on the detection of X-rays produced by the interaction of energetic charged particles (usually protons) with the electrons of the atoms in the target. In particular, an inner shell of the atom may be ionised and the vacancy is promptly filled by an electron from the outer shell; the difference between the two binding energies of the electron can be released in the form of an X-ray, the energy of which is therefore characteristic of the emitting atomic species. Depending on the shell in which the original vacancy is created, one has K-, L- or M-series X-rays (Figure 1). For a given series (K, L or M), X-ray energies are an increasing function of the atomic number of the emitting element. By detecting these X-rays (generally through Si(Li) detectors), the atomic elements present in the target can be identified and their concentration measured, since the number of X-rays emitted by the atoms of a species is proportional to its abundance in the target.

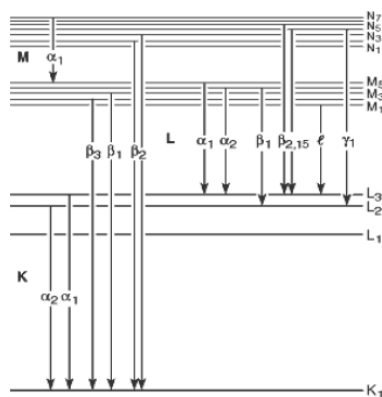


Figure 1 Partial energy level scheme with the most intense X-ray transitions
(http://xdb.lbl.gov/Section1/Sec_1-2.html)

3.2 PIXE Experimental Set-up

Projectiles for PIXE technique include protons, α -particles and even heavy ions. However, 2-3 MeV energy protons are generally preferred for most of the applications. A small particle accelerator is used to generate these projectiles. A single-ended Van de Graaff accelerator, with a continuously moving belt to transport charge to the terminal in order to maintain it at a potential of 2-3 MeV in a tank under high pressure, is the most popular particle accelerator. Protons with 2-3 MeV energy and helium ions with 4-6 MeV energy can be generated by such an accelerator. This machine can yield high currents up to several hundred μA .

Later small tandem accelerators, requiring only half the voltage of a conventional machine, were developed for the applications of PIXE and have become the most sought after machines commercially because of their reduced size and cost. In this accelerator, a very high positive voltage maintained at the geometric centre of the pressure vessel imparts energy to the negatively charged ion produced by the source. While reaching the high voltage mid-terminal region some electrons are stripped from the negative ion, thereby making it positive. This positive ion is then accelerated away by the high positive voltage towards the extreme end of the tank which is at ground potential. The accelerator thus has two stages of acceleration, first pulling and then pushing the charged particles. For PIXE analysis, a tandem machine with a terminal voltage of 1.5 MV is used to produce protons with 3 MeV energy. The vacuum inside the accelerating tube is maintained by using a combination of cryo-pumps, turbo pumps, and titanium ion pumps at regular intervals over the length of the beam line.

The beam coming from the accelerator first passes through a bending magnet and is then stabilized by making it pass through a slit. Slight energy variations within the accelerator can alter the deflection caused by the bending magnet. This change in the currents intercepted by the left and the right edges of the slit generates a differential signal which is amplified and used in a feedback loop to control the primary operating voltage of the accelerator. Electrostatic and magnetic steering elements are then used to direct the beam axially down the desired beam-line evacuated to about 10^{-6} mbar. The beam finally enters into the target chamber.

PIXE experimental set-up is shown in Figure 2. The samples are usually irradiated in vacuum since this allows the determination of even the low Z elements and also provides better detection limits when compared to irradiation at atmospheric pressure. A properly collimated beam is allowed to enter the target chamber and impinge on the sample placed on the sample holder. A sample manipulator connected to the top port of the target chamber makes it possible to avoid the frequent opening and re-evacuation of this chamber. By rotating the sample manipulator in the desired direction, a large number of samples and standards can be irradiated under vacuum. The sample here could be typically a film of biological material deposited on a thin pure backing foil or an aerosol filter or a thick pellet. Thin targets allow the beam to pass through them with only a fractional loss of energy and hence a Faraday cup is included in the set-up to monitor the beam current. Thick targets stop the beam completely and hence require the use of a charge integrator coupled directly to the target holder in order to monitor the beam current. X-rays emitted from the sample are detected using a Si(Li) detector, which has high efficiency in the X-ray energy region of interest (2-20keV) with a considerably good energy resolution. The signals from the detector preamplifier are processed with an amplifier, enabling pile-up rejection, and then fed into an ADC and MCA. The obtained data is then represented as a spectrum using a computer software. Spectral data is then transferred to a personal computer where further data analyses are carried out.

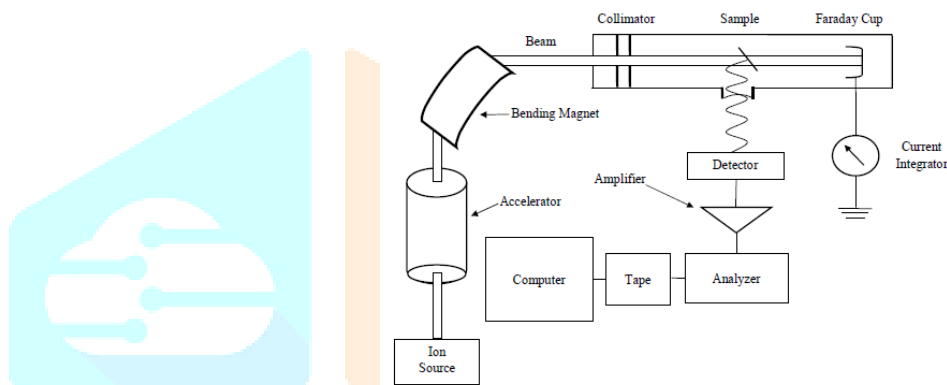


Figure 2 Schematic representation of PIXE experimental set-up [12]

A typical PIXE spectrum is shown in Figure 3. It consists of several characteristic x-ray peaks superimposed on a background which arises due to a variety of atomic bremsstrahlung processes and also due to gamma rays from nuclear reactions induced by the beam. This spectrum is a sum of contributions of the different elements present in the target irradiated: K X-rays from the lighter elements, K and L X-rays for the medium-Z elements, M and L X-rays for the higher-Z ones.

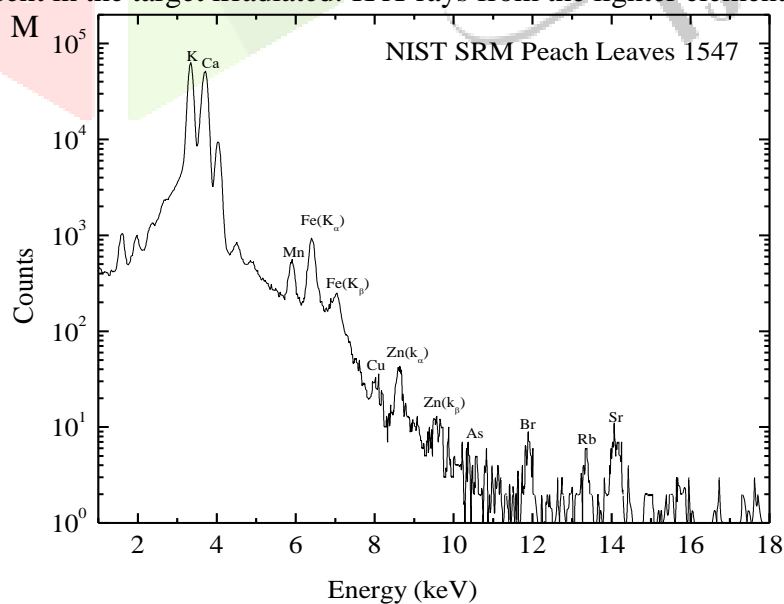


Figure 3. PIXE Spectrum of Peach Leaves (NIST 1547)

4 Background Radiation

PIXE spectrum mainly consists of a series of X-ray peaks superimposed on a broad continuum background in the low energy region and includes a slowly rising tail extending towards the high energy side of the spectrum. The three processes that mainly contribute to background in an ion induced X-ray spectra are

- i) Bremsstrahlung caused by secondary electrons ejected from the target atoms due to bombardment by the primary ion beam.
 - ii) Bremsstrahlung due to primary ions themselves.
 - iii) Compton scattering of γ -rays in the X-ray detector produced as a result nuclear reactions.
- i) Secondary electron bremsstrahlung (SEB): This is due to the acceleration or deceleration of charged particles in the presence of electric fields. SEB is due to the interaction between the target nuclei and electrons which have been ejected from the target atoms under the bombardment of primary ion beam. This dominates in the low energies of the spectrum and decreases more rapidly at the high energy side.
 - ii) Projectile bremsstrahlung: This is due to the interaction between the primary ion beam and the target nuclei. This bremsstrahlung represents a significant and perhaps dominant contribution to the background intensity for the X-ray region above 15 keV approximately.
 - iii) γ -ray back ground: Particle induced nuclear reactions dominate when low Z elements are present in the specimen at higher concentrations or when heavy ions are used to excite the specimen.

5 PIXE Spectra Analysis

In general, analysis of PIXE spectra can be done by any one of the following methods:

- a) Relative method: This method involves the use of standards
- b) Standard less or fundamental parameters approach: This method involves the use of fundamental physical parameters in combination with experimentally determined efficiency curve, knowledge on transmission filter and the sample characteristics.

For the quantitative analysis of PIXE spectra, fundamental parameters approach is the most widely used approach (Figure 4). The physical processes that are important for this method are as follows:

- i) A series of elastic and inelastic collisions occur between the incident projectile and the target atoms along the projectile's path.
- ii) The energy of the projectile decreases along its trajectory in the target depending on its capacity to penetrate within the target medium (stopping power).
- iii) Emission of characteristic X-rays by the ionized target atoms occurs in accordance with the X-ray production cross section.
- iv) Finally, attenuation of emitted X-rays takes place in the target material.

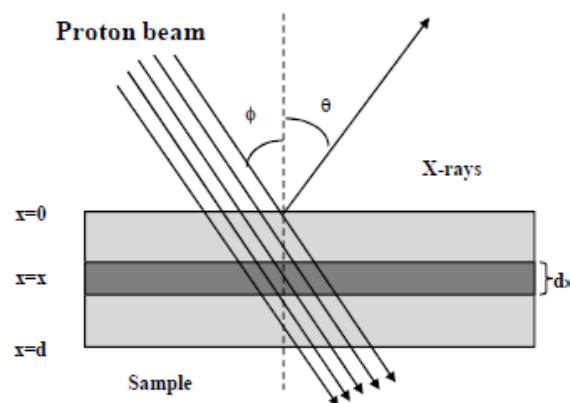


Figure 4. Schematic representation of PIXE analysis for finite thickness sample

In general, in the case of PIXE analysis X-ray yield Y_i for the characteristic X-ray of the i^{th} element in the specimen is given by [12]

$$Y_i = \frac{Q}{e} \int_0^d C(x) \sigma_i(E(x)) e^{-\frac{\mu x}{\cos\theta}} dx \dots \dots \dots (3)$$

where

Q = Total amount of the incoming particle charge

$C(x)$ = Concentration profile of the i^{th} element which is constant

σ_i = X-ray production cross section of the i^{th} element

$E(x)$ = Energy loss of the projectile while passing through the sample, calculated by

$$E(x) = \int_0^x S(E) dx \text{ where } S(E) = \frac{dE}{dx}$$

$S(E)$ = stopping power and μ = X-ray attenuation

Relationship between X-ray intensity (I_i) and concentration (C_i) of i^{th} element is given by

$$I_i = Q C_i K_i \dots \dots \dots (4)$$

where K_i = calibration constant which is independent of the sample if both geometry and matrix do not change and is given by

$$K_i = \varepsilon \int_0^d \sigma_i(E(x)) e^{-\frac{\mu x}{\cos\theta}} dx \dots \dots \dots (5)$$

The precision and accuracy of PIXE spectra analysis by this method are greatly influenced by the following parameters which are associated with the experimental set-up: i) Incident projectile energy (E_0) ii) Total number of particles bombarding the specimen i.e., total accumulated charge (Q) iii) Detector efficiency (ε) iv) Matrix composition v) Statistical uncertainty in the determination of area under characteristic X-ray peak.

6 Applications of PIXE

Applications of PIXE as a tool to analyze materials are probably only limited by our imaginations. Owing to its numerous capabilities and desirable features, PIXE has found application in the trace elemental analysis of samples from almost every conceivable field of scientific or technical interest like biomedicine, environment, geology, archaeology, materials science, forensic studies and industrial applications. A brief note on the diverse kind of materials that can be analyzed using PIXE is enumerated below:

6.1 Biological Samples

PIXE is a promising analytical tool for biological samples because of its non-destructive nature and ability to analyse small quantities of sample. Abundant work has been carried out successfully to analyse biological samples such as body fluids (blood and urine), tissues, hair, nail, bone, skin etc [13- 17]. With the increase in several types of cancers more attention has been focussed towards the analysis of cancer afflicted organs. Among all the elements observed in the analyzed organs, the elements copper, iron, zinc, selenium, chromium, nickel, and arsenic are generally accepted as the vital elements that influence cancer.

6.2 Plant Materials

Plants materials in general and medicinal plants in particular have been extensively studied by PIXE to monitor environmental pollution and understand their curative ability in treating various ailments respectively. The use of plants as atmospheric pollution biomonitors is a more practical, in-expensive and yet reliable means of air quality status assessment in any region. [18]. Medicinal plants have served as rich sources of many trace elements for man and it is suggested that this is an important factor in the curative effect of these plants. PIXE is a well suited method to analyze different parts of herbal plants to know their inorganic constituents and to decide the appropriate dose for the treatment of a particular disease [19-21].

6.3 Aerosol Samples

One of the most important applications of PIXE is in atmosphere research [22-23] to analyze aerosol samples for their trace elemental content and composition of the particulate matter (PM) as a function of particle size. Establishing the elemental composition of aerosols would help to identify the sources (natural or anthropogenic) and consequently monitor their health impacts. Studies of this kind can be used to for scientifically defensible air quality management. Air particulate matter is collected by pumping air through a

suitable filter or a cascade impactor. Particles with aerodynamic range 0.1-10 μ m are deposited on a Mylar foil or a Nuclepore filter (<1mg/cm²) to minimize the matrix effects. Such samples are ideal for PIXE.

6.4 Sediment Samples

Pollutants and toxic elements in the environment are also determined by analyzing soil and sediment samples. Trace pollutants present a major threat to humans, animals and plants. In a certain study elemental concentrations of contaminated Kakinada Bay sediment samples were determined by PIXE. Various hazardous elements followed the order of concentrations As < Co < Zn < Cr < Ba < Mn < Fe as determined in sediment samples. The increase in hazardous elemental concentrations when compared to previous studies is attributed to industrial effluents from textiles industries and anthropogenic activities around the Godavari peninsula and Kakinada Bay [24].

6.5 Archaeological Samples

Chemical composition of artifacts reveal the clarifications on provenance studies which tell whether the artifacts belong to the same or different group or origin, This helps to identify the source or actual origin of these artifacts. The novel external proton beam PIXE technique is a highly suitable for elemental constituents in archaeological samples directly. Dasari et al [25] employed external PIXE to determine elemental concentrations of Ti, V, Cr, Mn, Fe, Ni, Cu, and Zn and these elemental content are further used for grouping the artifacts using multivariate statistical cluster analysis (CA) methods.

6.6 Semiconducting Materials

Semiconducting materials are an integral part of electronic devices having innumerable applications. Hence, it is very important to study their actual properties and the alteration in their properties when subjected to extreme conditions so as to know their effectiveness in a particular application. Moreover, studies on material modification can be carried out by measuring trace contamination in semiconducting materials. PIXE has been extensively used to determine the presence and concentrations of elements acting as impurities in some semiconducting materials, analyze thin films for photovoltaic applications and high T_c superconductors.

REFERENCES

1. Chadwick, J. "LIV. The γ rays excited by the β rays of radium." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 24.142 (1912): 594-600.
2. Johansson, Thomas B., Roland Akselsson, and Sven AE Johansson. "X-ray analysis: elemental trace analysis at the 10– 12 g level." *Nuclear Instruments and Methods* 84.1 (1970): 141-143.
3. Johansson, Sven AE, and Thomas B. Johansson. "Analytical application of particle induced X-ray emission." *Nuclear Instruments and Methods* 137.3 (1976): 473-516.
4. Maenhaut, W., and H. Raemdonck. "Accurate calibration of a Si (Li) detector for PIXE analysis." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 1.1 (1984): 123-136.
5. Folkmann, Finn. "Analytical use of ion-induced X-rays." *Journal of Physics E: Scientific Instruments* 8.6 (1975): 429.
6. Johansson, Sven AE, and John L. Campbell. "PIXE: A novel technique for elemental analysis." Wiley, Chichester (1988).
7. SAE Johansson, JL Campbell, KG Malmquist. "Particle-Induced, X. "ray emission spectrometry". Eds. Wiley, New York (1995).
8. Campbell, J. L., and J. A. Cookson. "PIXE analysis of thick targets." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 3.1-3 (1984): 185-197.
9. Watt, F., et al. "Nuclear microscopy of biological specimens." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 54.1-3 (1991): 123-143.
10. R.D. Vis, R.D (ed.), Proceedings of the Fifth International Conference on Particle Induced X-ray Emission and Its Analytical Applications, Nucl. Instr. Meth., B49(1990).
11. Uda M (ed.), Proceedings of the Sixth International Conference on Particle X-ray Emission and Its Analytical Applications, Nucl. Instr. Meth., B75 (1993).
12. Instrumentation for PIXE and RBS, IAEA, December, 2000, Austria, (https://www-pub.iaea.org/MTCD/Publications/PDF/te_1190_prn.pdf).

13. Raju, GJ Naga, P. Sarita, and K. S. R. Murthy. "Comparative trace elemental analysis of cancerous and non-cancerous tissues of rectal cancer patients using PIXE." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 404 (2017): 146-149.
14. Guntupalli, J. Naga Raju, et al. "Trace elemental analysis of normal, benign hypertrophic and cancerous tissues of the prostate gland using the particle-induced X-ray emission technique." *European journal of cancer prevention* 16.2 (2007): 108-115.
15. Sarita, P., GJ Naga Raju, and S. Bhuloka Reddy. "Studies on changes in trace elemental content of serum of uterine cervix cancer patients using PIXE." *Journal of Radioanalytical and Nuclear Chemistry* 302.3 (2014): 1501-1506.
16. Pradeep, A. S., et al. "Trace elemental distribution in the scalp hair of bipolars using PIXE technique." *Medical hypotheses* 82.4 (2014): 470-477.
17. Pallon, Jan, et al. "Optimization of PIXE-sensitivity for detection of Ti in thin human skin sections." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 231.1-4 (2005): 274-279.
18. McClenahen, James R., John P. Vimmerstedt, and Amy J. Scherzer. "Elemental concentrations in tree rings by PIXE: statistical variability, mobility, and effects of altered soil chemistry." *Canadian Journal of Forest Research* 19.7 (1989): 880-888.
19. Devi, K. Nomita, H. Nandakumar Sarma, and Sanjiv Kumar. "Estimation of essential and trace elements in some medicinal plants by PIXE and PIGE techniques." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 266.8 (2008): 1605-1610.
20. Rajan, Jay Prakash, et al. "Trace elements content in the selected medicinal plants traditionally used for curing skin diseases by the natives of Mizoram, India." *Asian Pacific journal of tropical medicine* 7 (2014): S410-S414.
21. Raju, GJ Naga, et al. "Estimation of trace elements in some anti-diabetic medicinal plants using PIXE technique." *Applied radiation and isotopes* 64.8 (2006): 893-900.
22. Oswal, M., Kaur, R., Kumar, A., Singh, K. P., Kumar, S., Mohanty, B. P., & Kumar, S. (2012). Trace element analysis of aerosol samples using PIXE technique. *International Journal of PIXE*, 22(03n04), 271-285.
23. Tadros, C. V., Crawford, J., Treble, P. C., Baker, A., Cohen, D. D., Atanacio, A. J., ... & Roach, R. (2018). Chemical characterisation and source identification of atmospheric aerosols in the Snowy Mountains, south-eastern Australia. *Science of The Total Environment*, 630, 432-443.
24. Dasari, K.B., Ratna Raju, M., Lakshminarayana, S., J. Radioanal. Nucl. Chem., 307 (2016) 875.
25. Dasari, K.B., Acharya, R., Ray, D.K., Lakshmana Das N., X-ray Spectrometry, 46 (2017) 180-185.