Particle air pollution monitoring with nuclear analytical techniques: challenges and opportunities

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Abstract

Air pollution through fine and ultra-fine particles is a major threat to human health in cities of developed and especially of developing countries. In certain countries, even higher levels of fine particles occur in the indoor environment due to open stove cooking and heating. Fine and ultra-fine particles penetrate deeply into the lungs and can remain there for a substantial time. The WHO estimated the global attributable mortality risk due to particle urban air pollution to about 800 000 excess deaths per year and to 1.6 million excess deaths per year due to particle indoor air pollution in urban and rural areas.

Fine particle sampling with filters is now common in many countries in Asia. Through the International Atomic Energy Agency (IAEA) regional project on air pollution, particulate matter (PM) monitoring stations have been set up in the Asia Pacific region, in addition to stations from national authorities. Large numbers of particle samples in the $PM_{2.5}$ and $PM_{10-2.5}$ ranges have so far been collected and analyzed by nuclear analytical methods, namely ion beam analysis techniques, e.g. particle induced X-ray emission (PIXE), neutron activation analysis (NAA), and X-ray fluorescence spectrometry (XRF). Large data sets generated have been used for characterization and apportionment of particulate matter sources which are key to effective understanding, control and management of particulate matter air pollution. This paper reviews the opportunities and applications of nuclear analytical techniques in air pollution monitoring and the contribution from the experience of the IAEA.

Keywords: Neutron activation analysis; particle induced X-ray emission; X-ray fluorescence spectrometry; source identification; source apportionment.

1. Introduction

Urbanization and associated industrial development and growth in mobility have deteriorated air quality and intensified air pollution in densely populated areas throughout Asia. The severity of the air pollution problems in Asian cities reflects the level and speed of development. Urban air pollution poses a significant threat to human health and the environment and the quality of life of millions of people. Many cities in Asia now have to take action to enhance their institutional and technical capabilities to monitor and control air quality and implement preventive measures in order to reduce the risks that air pollution poses to their citizens. In the past, the major causes of environmental degradation occurred sequentially rather than simultaneously. Nowadays many Asian cities suffer the pressure of a combination of the different driving forces, each with a greater intensity than has occurred elsewhere or in the past and without a sufficiently well-developed institutional capacity and financial resources to control them. As a consequence, the ability of many cities in the region to cope with the combined pressures is often exceeded leading to deterioration of environmental quality.

A major compound in urban air pollution is particulate matter (PM), which can be coarse, fine or ultra-fine. In many Asian countries PM concentrations exceed promulgated air quality standards, e.g. US EPA standards adopted in some countries (US EPA, 2004), and historic WHO guideline values (WHO 1972; 1979; WHO/EURO 1987). Current PM concentrations (e.g. TSP, PM_{10}) indicate the potential of significant health impacts, since WHO's guideline values for PM have been replaced by exposure-response relationships (WHO, 2000). Concentrations of particulate polycyclic aromatic hydrocarbons (e.g. benzo[a]pyrene) and heavy metals (e.g. lead, cadmium, chromium, nickel) are a matter of concern since these compounds are either carcinogenic or highly toxic.

Particles occur in the atmosphere with equivalent atmospheric diameters from less than 100 nanometres to fifty micrometers and above and with widely varying residence times depending on their size. Particulate matter with diameter less than 2.5 μm ($PM_{2.5}$) is generally referred as fine particulate matter. Medical researchers have defined the respirable fraction as the mass of inhaled particles, which penetrate, to the unciliated airways. PM10 is defined as the mass concentration of particles collected with a 50% cut-point at an aerodynamic particle diameter of 10 micrometers. The total suspended particulate (TSP) fraction is all suspended matter, usually with diameters less than about 50 μm.

Fine particles ($PM_{2.5}$) are small enough to penetrate deep into the lungs and hence have significant health implications for humans. Excess deaths due to fine particulate air pollution are estimated around 800,000 globally per year. In a 2002 report of the Air Pollution in the Megacities of Asia project (APMA, 2002) it was quoted that in Bangladesh's capital Dhaka air pollution annually causes 3,580 premature deaths, 10 million restrictive activity days and 87 million respiratory symptom days at an economic cost of US$ 60-270 million.

For rational air quality management, the sources of particle air pollution must be known qualitatively. An essential shortcoming of current practices in air quality management in Asia is the lack of reliable emission estimates or inventories for PM and gaseous compounds as well (SF 2004). For this reason, the use of nuclear analytical techniques (NATs) for particulate matter analysis is discussed here as a means for source identification and source apportionment.

The paper is organized as follows. Section 2 describes the challenges in Asian cities relating to particle air pollution. In section 3 nuclear analytical techniques are described together with their role in particle monitoring, their strengths and limitations. Section 4 provides some practical examples of source identification and apportionment.

2. Challenges in Asian cities

The Strategic Framework note several challenges in Asian cities relating to policies and regulatory issues, magnitude of air pollution, emissions inventories and source apportionment.

2.1. Policies and regulatory issues

Challenges for air quality management policies in Asia include among others:

- Low government commitment;
- Limited co-ordination and sectoral integration;
- Limited collaboration between different agencies;
- Poor institutional capacity;
- Absence of appropriate review mechanisms;
- Regional differences in regulation of emission sources;
- Deficiencies in setting air quality standards
- Lack of
    - stakeholder participation;
    - up-to-date emission standards;
    - monitoring and quantitative data on air quality and its impact on human health and the environment;

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Challenges regarding law enforcement and implementation of an integrated air quality management system in Asia include among others:

- Conflicts through duplicated responsibilities
- Inappropriate technical equipment and ignorance about its usability
- Prevalence of *ad hoc* awareness raising with a focus on raising alarm
- Poor information on public participation
- Deficiencies in information dissemination
- High cost of awareness raising programmes
- Design and implementation of AQM strategies often based on incomplete knowledge
- Potential of misinterpretation of air quality reporting and information
- Insufficiency of adequate communication strategies among stakeholders
- Inadequate regulatory, planning, technical, social, institutional, and financial capacity for AQM
- Lack of
  - Staff with specialized skills
  - Reporting to upper management in agencies
  - Inter-Agency communication.

2.2. Particulate matter concentrations

Total suspended particulate (TSP) matter concentrations in Asian cities exceed the WHO guidelines value range of 60-90 µg m^{-3} substantially (APMA 200; WHO 1979). For PM_{10} the US EPA standard of 50 µg m^{-3} is also often exceeded in cities of China and India. This is the more serious since even compliance with the US EPA standard still bears a significant risk of health impacts according to the WHO exposure-response relationships. Impacts such as excess daily mortality and hospital admissions due to cardio-respiratory conditions are still possible to occur.

2.3. Emissions inventories and source apportionment

According to the SF, challenges in Asia include among others a lack of

- emission inventories and quality assured emission data;
- source apportionment;
- periodical update of emissions standards.

Lack of source apportionment does not allow estimate the relative contributions of different source types such as special industrial plants, traffic, commercial and residential contributions. Therefore, an air quality manager cannot be sure that his/her decisions with regards to emission reduction are the most efficient ones, e.g. if a minor source becomes regulated while a major source does not.

3. Role of nuclear analytical techniques in PM monitoring

3.1. PM sampling

A particulate sampler essentially consists of a vacuum pump and a filter, which is usually operated in a standard shelter to collect a 24-h sample. GENT samplers are a good example of sampling units that collect particulate matter in two fractions, fine ($PM_{0-2.5}$) and coarse ($PM_{2.5-10}$) (Maenhaut et al., 1994; Hopke et al., 1997; Markowicz et al., 2002). A balance is used to weigh the filter to measure the total amount of PM collected. Due to the small amount of material collected, the filters are weighed on a microbalance.

The average PM10 concentration for the sample period is determined by dividing the net weight gain of the filter over the sample period by the total volume of air sampled, corrected to the standard temperature of 25 ºC and standard pressure of 1013 hPa. Other specifications apply for flow rate control and measurement, device calibration, filter media characteristics and performance, filter conditioning before and after sampling, filter weighing, sampler operation, and correction of sample volume to US EPA reference temperature and pressure.

In operation, air is sucked into the sampler through a Teflon or polycarbonate filter by a vacuum pump. Particulate mater is collected on the filter surface. For heavily polluted atmospheres, shorter sampling periods are used, which could be staggered over a 24-hour period. A flow-rate indicator determines the volume of air sampled.

3.2. PM nuclear analysis methods

Airborne particulate matter retained on the filter may be examined or analysed chemically by a variety of methods. In this paper, only nuclear analytical techniques (NATs) are considered because of their advantages in analysing many elements in air particulate matter non-destructively and simultaneously. The key three NATs for analysis pf particulate matter in air are:

(i) Neutron activation analysis (NAA);
(ii) X-ray fluorescence (XRF); and
(iii) Ion beam analysis (IBA).

3.3. Description of NATs

3.3.1 Neutron Activation Analysis

In typical NAA, a sample is exposed to a high flux of thermal neutrons in a nuclear reactor or accelerator. Stable nuclides in the sample (target nucleus) undergo neutron capture reactions. The radioactive nuclides (compound nucleus) produced in this activation process will, in most cases, decay through the emission of a beta particle (ß$^{-}$) and gamma ray(s) with a unique half-life. After the sample has been removed from the reactor it continues to emit radiation as the radioactive isotopes decay. A high-resolution gamma-ray spectrometer is used to detect these "delayed" gamma rays from the artificially induced radioactivity in the sample for both qualitative and quantitative analysis. The principle of the method is illustrated in figure 1.

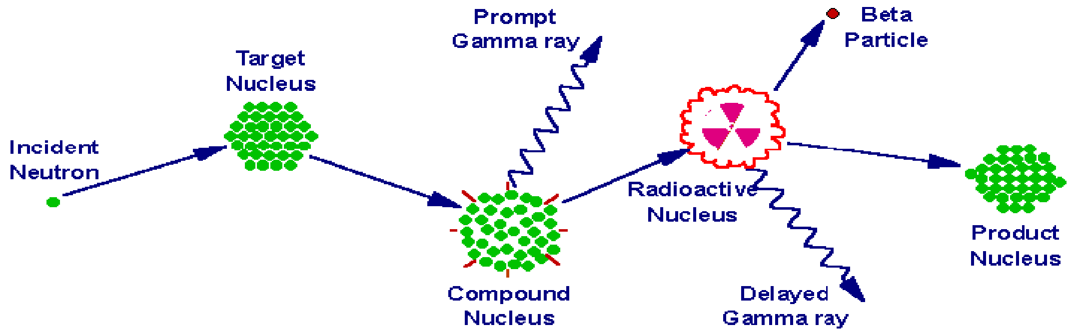

Figure 1: Sequence of events that occur during the most common type of nuclear reaction used for neutron activation analysis.

Source: Glascock (2004).

Standard materials of known composition are irradiated at the same time for calibration. The spectrum of energy of the gamma rays determines the specific isotopes present in the sample. The intensity of the gamma rays is proportional to the amounts of elements present. Typically 5 counting regimes are required to detect these elements. The counting regimes are applied after 300 s, 1 hr, 10 hr, 4 days and 15 days. It is highly sensitive (ppb range for many elements), though it does not quantify elements such as silicon, nickel, cobalt, and lead. Typical elemental detection limits range from 0.01 to 10 ng m^{-3}. Individual elemental detection limits can be found in US EPA (1999a). For more detailed information on NAA analysis of PM analysis see Weizhi (2000).

NAA is a simultaneous, multi-element method that can be used to measure more than 40 elements and does not generally require significant sample preparation. It is a non-destructive technique and does not require the addition of any foreign materials to the sample for analysis; thus, the problem of reagent-introduced contaminates does not occur. Analysis by NAA is compatible with sampling by high-volume (TSP; PM10) and dichotomous samplers.

3.3.2. X-ray Fluorescence Spectroscopy

When a primary X-ray from an X-ray tube or a radioactive source hits a sample of material, the X-ray can either be absorbed by an atom or scattered through the material. The process in which an X-ray is absorbed by an atom by transferring all of its energy to an innermost electron is called the "photoelectric effect." If the primary X-ray had sufficient energy, electrons are ejected from the inner shells, creating an excited atom with vacancies on inner shells. These vacancies present an unstable condition for the atom. As the atom returns to its stable condition, electrons from the outer shells are transferred to the inner shells and in the process emit a characteristic X-ray whose energy is the difference between the two binding energies of the corresponding shells. Because each element has a unique set of energy levels, each element produces X-rays at a unique spectrum of energies, allowing one to identify the element and to measure the elemental composition of a sample (adapted from AmpTek, 2004). The measuring of compounds in samples by XRF is illustrated in figure 2.

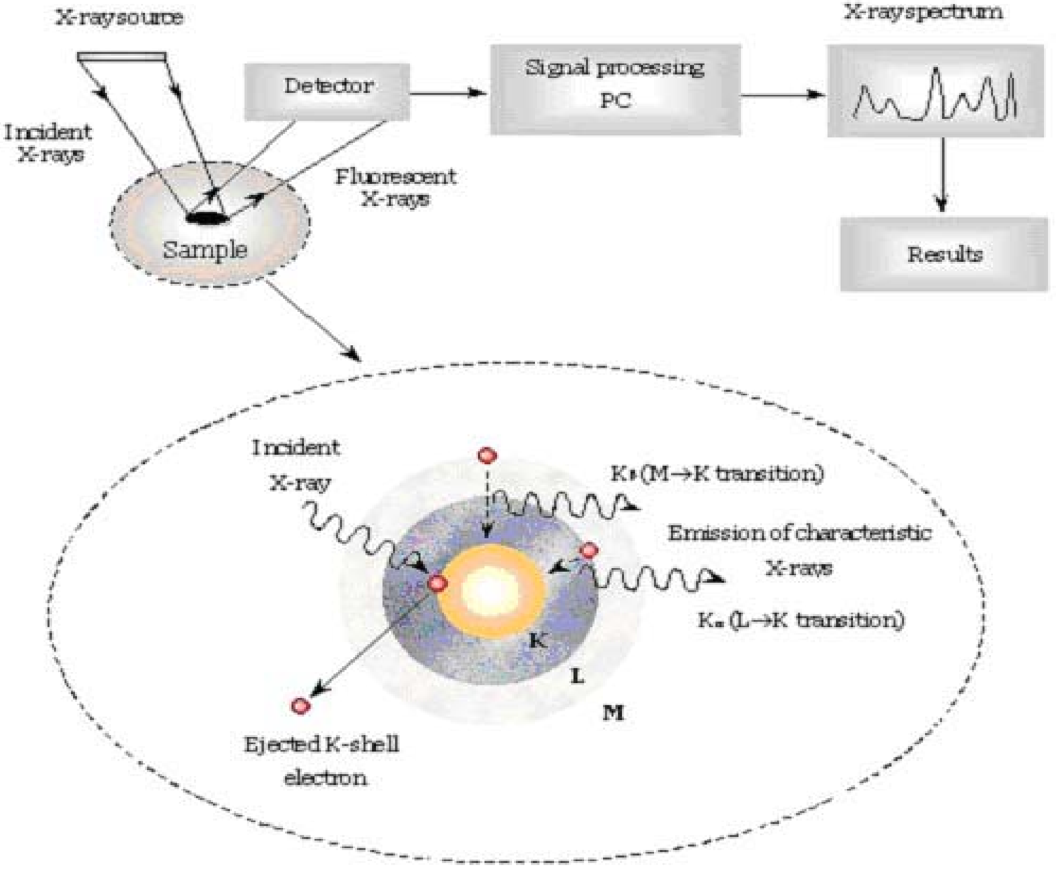

Figure 2: The principle of XRF and the typical XRF detection arrangement. Source: Papachristodoulou (2002).

In XRF spectroscopy, many elements can be measured simultaneously. XRF is non-destructive and requires minimal (or no) sample preparation - the filter is inserted directly into the instrument for analysis. This technology is relatively inexpensive. Because quartz filters used in high-volume samplers cause high background XRF analysis, filters used in the dichotomous samplers are preferable.

X-ray fluorescence spectrometry can be used for all elements with atomic numbers from 11 (sodium) to 92 (uranium). Typical elemental detection limits for this method range between 2 and 2000 ng m^{-3} (US EPA, 1999b). XRF depends on the availability of excellent PM standards. Two laboratories are currently main suppliers for PM standards:

- National Institute of Standards and Technology (NIST, 2004);
- Institute for Reference Materials and Measurements (IRMM, 2004).

These PM standards are well suited to solve many problems. More details on XRF may be found in Jenkins (1999), Kalnicky and Singhvi (2001), and Van Grieken and Markowicz (2002).

3.3.3. Ion Beam Analysis (IBA)

Ion Beam Analysis (IBA) is based on the interaction, at both the atomic and the nuclear level, between accelerated charged particles and the bombarded material. When a charged particle moving at high speed strikes a material, it interacts with the electrons and nuclei of the material atoms, slows down and possibly deviates from its initial trajectory. Electrons in the inner shells of the atom (predominantly the K and L shells) are given enough energy to cause them to be ejected, resulting in an unstable electron atomic configuration. Electrons from higher shells in the atom then 'drop down' to fill these vacancies, and in so doing, give off excess energy in the form of X-rays. The energies of these X-rays are characteristic of the element and therefore can be used to identify the elements which constitute the sample material. IBA comprises a suite of four techniques:

- Particle induced X-ray emission (PIXE);
- Particle induced gamma ray emission (PIGE);
- Proton elastic scattering analysis (PESA); and
- Rutherford Backscattering Spectrometry (RBS).

These techniques are used simultaneously as key analytical tools to assess PM pollution on a regular basis. Most importantly, the choice of analytical method depends on the inorganic compounds of interest and the detection limits desired. Using the four different analysis techniques, IBA can measure more than 40 elements (H – U).

IBA is illustrated in figure 3.

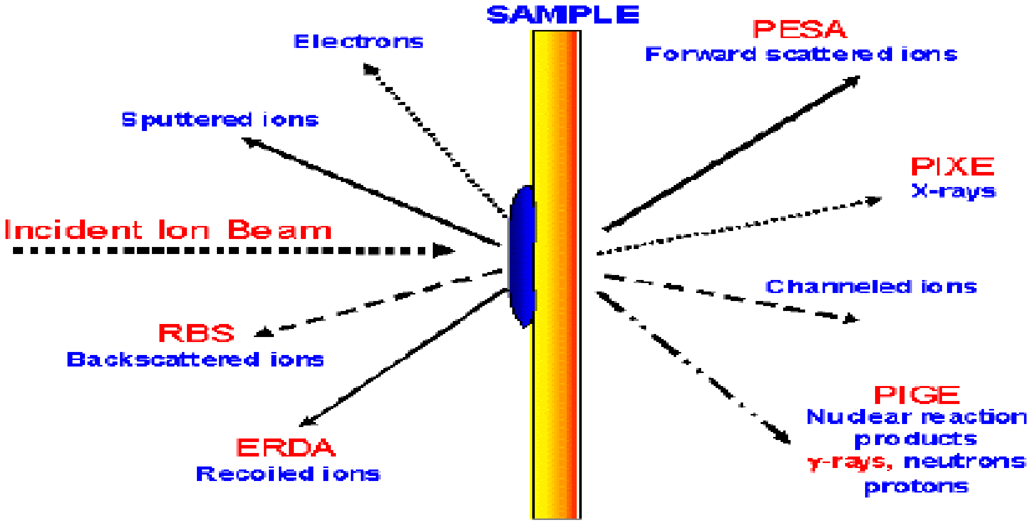

Figure 3: Ion beam analysis methods. Source: Fernández (2004)

PIXE Particle (Proton) Induced X-ray Emission Analysis. PIXE is a powerful and relatively simple analytical technique that can be used to identify and quantify trace elements typically ranging from Na to U. Sample irradiation is usually performed by means of 2-3 MeV protons produced by an accelerator. X-ray detection is usually done by energy dispersive semiconductor detectors such as Silicium (Lithium) or High Purity Germanium detectors. This multi-elemental analysis technique can measure more than 30 elements in short times due to higher cross-sections as compared to XRF. Analysis by PIXE typically involves collecting $PM_{2.5}$ by dichotomous samplers. With the addition of PIGE and PESA, IBA allows for the detection of light elements that is useful for finger printing, source apportionment and estimation of organic carbon. Specific experimental set-ups are used to measure air filters semi-automatically (Cohen et al., 1996; Cohen, 1996; Cohen et al., 2000; Cohen, 2000; Trompetter et al. (2000a; b). Typical detection limits range from 1 to 50 ng m^{-3}. For more detailed information on PIXE and PIGE of APM analysis see Cohen et al. (2000) and Cohen (2000).

The remaining three methods are used simultaneously to achieve additional information on elements that can not or hardly be measured with PIXE.

PIGE Particle (Proton) Induced γ-ray Emission Analysis. When a charged particle (typically protons) approaches the nucleus of a target atom, the Coulomb force usually repels it. However when the incident particle has enough energy to overcome the repulsive Coulomb force a charged particle then penetrates through the electrostatic barrier into the nucleus, resulting in interactions with the nuclear forces. During that process, a number of interactions occur, depending on the energy of the incident particle and the type of target nucleus. Typically, a nuclear reaction will occur, resulting in the emission of high energy x-rays (x-rays emitted from nucleus are for historical reasons called gamma rays) and other nuclear particles. In the case of PIGE technique, emitted gamma rays are of particular interest as their energies are characteristic of the element and are therefore used to fingerprint elemental composition while yields are used to quantify elemental concentrations. The detection of the emitted gamma rays is usually done by large volume Ge detectors. PIGE is typically run in conjunction with PIXE and RBS and is used to quantify concentrations of low Z elements such as: B, Li, F, Na, Mg and Al (Cohen, 1993). Detection limits vary from element to element and are in the range of about a hundred ng m^{-3}, the precision is around a few %.

PESA Proton elastic scattering analysis.PESA is similar to Rutherford backscattering analysis (RBS) but in forward direction and is used to measure H to help to distinguish between elemental and organic carbon is samples Hydrogen in the air particulate matter collected on a filter can be measured providing the filter material is free of hydrogen. Hence Teflon filters consisting of only carbon and fluorine are hydrogen free whereas polycarbonate filters contain much more hydrogen on such filter materials. . The limit of detection is about 20 ng m^{-3}. A technical good description about PESA can be found in Cohen (1993).

RBS Rutherford Backscattering Spectrometry**.** In RBS, only backscattered ions are detected, and backscattering can only occur if the target atom's mass is heavier than that of the incident ion. RBS allows the measurement of C, N and O mainly. This information is mostly useful for charge calibration purposes. However, since RBS can measure the total carbon deposited onto filters, it is possible to distinguish between elemental and organic carbon using RBS. Typical limits of detection for the three elements are in the range of 100 – 400 ng m^{-3}; the typical precision is a few %. Additionally RBS can measure elemental depth profiles in materials up to approx. 1 – 2 µm depth with high resolution. In proton microprobe studies of PM, RBS can therefore provide additional information on individual particles. Technical descriptions of RBS used in fine particle pollution studies are published in Markwitz et al. (1997;1998a; b); Markwitz (2000) and Cohen (1995). Figure 4 shows a typical experimental setup (Trompetter and Markwitz, 2002).

ERDA Elastic Recoil Detection Analysis. ERDA is the measurement of recoiling atoms following elastic nuclear collisions at a glancing angle. ERDA) is the complementary technique to RBS and used mainly for profiles of very light ions such as hydrogen or deuterium in thin layers, and in the near surface region of materials. ERDA a popular technique for the determination of hydrogen in solids, and studies of polymer interdiffusion., but less so in environmental monitoring

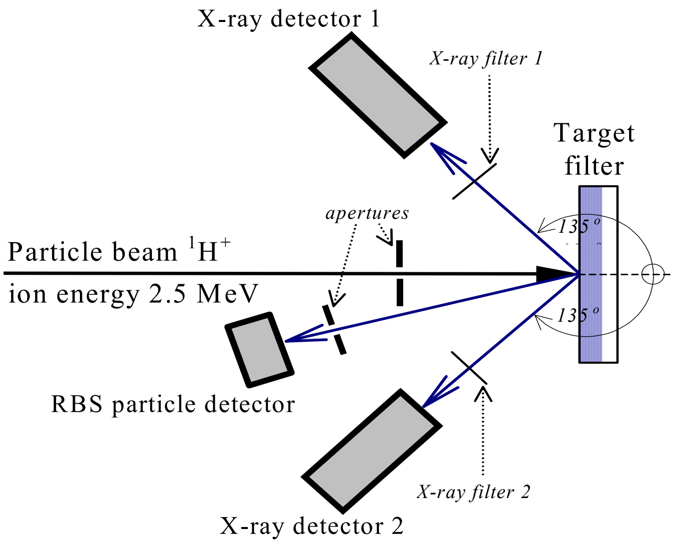

Figure 4: .Schematic of a typical experimental setup. Source: Trompetter and Markwitz (2002).

3.4. Advantages and disadvantages of NATs

Major technical advantages and disadvantages of the above-discussed analytical techniques are summarized in table 1 (US EPA (1999a;b); Markowicz et al., 2002)). While factors such as element specificity and sensitivity are critically important, considerations such as cost and throughput (the number of samples and number of elements to be determined per sample) are also important.

Apart from the technical disadvantages of NATs indicated in Table 1, the costs of establishing a dedicated system and the off-line nature of NATs are crucial disadvantages, which probably have limited the use of NATs for PM analysis in Asia. In addition, NAA needs access to a research nuclear reactor.

Current manufacturers of particle accelerators are High Voltage Engineering in The Netherlands (HVE, 2004) and National Electrostatics Corporation in the United States (NEC, 2004). Both companies offer 'cheap' bench-top accelerators that require approximately 10 m^2 of floor space in an air-conditioned building and costs about US$ 500,000. The dedicated beam line can be homemade, which is normally the case, or purchased from international organizations for approximately US$250,000. In summary, for less than US$ 1M, which would exclude the air-conditioned building, a dedicated machine can be purchased.

Cost-sharing among countries or commitments from donor agencies may help to overcome the first disadvantage for IBA and XRF.

The fact that PM has first to be collected on appropriate filter material by a PM sampler before it can be analysed means that

- no instant information is available;
- the information gathered on the filters is only relevant for a longer periods of time;
- the costs in monitoring due to time losses through shipping the samples to the analysis facility;
- turn around times of results are increased.

The turn around time, quality and cost-effectiveness are usually key for end-user who, on the other hand likes to know the sources and the contribution to a specific period in air pollution as quickly as possible.

Table 1: Technical advantages and disadvantages of nuclear analytical techniques used for PM analysis.

Method	Advantage	Disadvantage
NAA	• multielemental (Na – U) • non-destructive • minimal sample preparation • percent to ppb range • high sample throughput • well documented applications • quick, irradiation time less than 15 minutes • high sensitivity • can handle small sample sizes (< 1 mg)	• some elemental interferences • standard sample matrix corrections • slow, requires multiple counting regimes to detect many elements • not cost effective for few samples • does not include all elements from Na – U • requires access to research nuclear reactor
IBA	• multielemental (H – U) • non-destructive • minimal sample preparation • quantitative • quick, typically 15 min per analysis • high sensitivity • can handle small sample sizes (< 1 mg) • cost effective for large sample numbers, more than 10.	• cheap (typically 40 elements for US$70 per filter) • standard/sample must match closely (matrix) • matrix offsets and background • impurities may be a problem • not cost effective for small sample numbers, less than 10. • requires access to particle accelerator
XRF	• multielemental (Na to U) • non-destructive • minimal sample preparation • shorter analysis time than NAA • high sensitivity for many elements • good accuracy and precision • automation possible • new large irradiation facility required	• standard/sample must match closely (matrix) • matrix offsets and background impurities may cause problems • analysis time longer than PIXE/IBA • particle size effects for low Z elements • inter-element interferences • blind spots due to limitations of excitation mode or overlapping X-ray lines

4. Examples of NAT applications

4.1. Source identification

Sources that emit PM can be identified by the elements that are present in the particles or on their surfaces. In order to be able to identify the specific sources unambiguously, key elements have to be measured since many elements originate from many different sources of pollutants. In assisting this task, information from large databases on elemental composition generated by NATs for the samples collected. These are available in the individual countries is applied. In the following, examples are given that link key elements to their origin.

In Australia, IBA/PIXE is used to identify the elements for identifying pollution sources, cf. Table 2 (Cohen, 2000).

Table 2: Sources of APM pollution in Australia as identified by IBA/PIXE. Source: Cohen et al. (2000).

Source	Elements
Motor Vehicles	H, Na, Al, Si, S, Cl, Fe, Zn, Br, Pb, elementary C
Smoke	H, Cl, K, Ca, elementary C
Soil	Al, Si, K, Ca, Ti, Mn, Fe
Seaspray	Na, S, Cl, K, Ca
Industry	H, P, S, V, Cr, Cu, Pb, elementary C

Based on this information, the following key elements have been identified as shown in Table 3:

Table 3: Key elements for APM sources in Australia, table 3. Source: Cohen et al. (2000).

Key element	Source
Al, Fe, Si	Motor Vehicles, Soil
Br, Zn	Motor Vehicles
Ca, K	Smoke, Soil, Seaspray
Cl	Motor Vehicles, Smoke, Seaspray
Cr, Cu, V	Industry
Elementary C, H	Industry, Motor Vehicles, Smoke
Mn, Ti	Soil
Na	Motor Vehicles, Seaspray
Pb	Industry, Motor Vehicles
S	Industry, Motor Vehicles, Seaspray

In Beijing, China, NAA is used to identify major PM pollution sources, summarized in table 4.

Table 4: Sources of APM pollution in Beijing as identified by NAA . Source: Weizhi (2000).

Source	Elements
Soil, flying ash	Al, Ba, Ca, Ce, Ey, Fe, Ga, Hf, La, Mg, Sc, Sm, Th, Ti, V
Refuse incineration	As, Cs, I, K, Rb, Sb, Se, Zn
Motor Vehicles and Coal Burning	As, Br, Co, Ga, Sb, Se, U, V, W
Seaspray	Cl, Na

PM pollution sources in Vietnam were also identified by NAA in table 5.

Table 5: Sources of APM pollution in Vietnam as identified by NAA. Source: Hien (2000).

Source	Elements
Vehicular Emissions	Br, Zn
Coal Burning	Se
Industrial processes	Ce, Co, Cr, Pb, Sb
Road dust	Al, Ti, V
Soil dust	Fe, Th
Biomass burning	K
Marine aerosols	Na, Cl
Mineral fly ash	Sc, La

4.2. Source apportionment

In order to assess the contribution of these sources to PM air pollution, source apportionment has to be performed. Measuring the elements of APM on exposed filters (i.e. fine and coarse filters) is only the first step in monitoring APM pollution. From experience of the participants of the IAEA regional project on air pollution, they were able to generate information on concentration levels of certain elements of importance for air quality management which were not being measured under national air monitoring programs. In addition the use of data can be maximized by generating information on pollutant sources. Interpreting the elemental results is regarded as at least as important as measuring the elements. Clearly, the elemental information itself, regardless how accurate and fine it is, does not deliver a result satisfactory for the end-use community. Once the elements have been identified, this also includes weighing of the filters to obtain the total mass and measurement of elemental carbon via light absorbing or reflecting devices, the element data has to be processed to identify the major sources of pollution. Grouping of elements of many filters, typically a minimum of 50 filters from one single location is required, to enable a meaningful identification of some sources of pollutants. The procedure to accomplish this is relatively easily to learn, however, requires a basic understanding of statistical processing. Analytical programmes are available to assist with this task, however, quite often the usage of spread sheets already delivers most important results. Once the sources of pollutants are identified, or at least 3 to 4 different sources have been found, information can be obtained regarding their apportionment (Hopke, 2000).

Both, the information about the identified sources of APM pollution and the source apportionment is what the end-user, typically a governmental organization being in charge of air pollution monitoring or the industry that must prove its industrial plant is operating within specifications, requires. Globally, some progress has been made in the past to raise an awareness of the capability of PM monitoring with nuclear technologies, but quite often the step from interpreting the elemental data in such a way that it becomes essential information for end-users has not been made to satisfaction. This is most significant in developing countries.

An example of source apportionment of fine and coarse APM collected in the urban Wellington region in New Zealand (June 1998 – June 1999) is shown in figure 5 (Trompetter et al. 2000b). For additional references highlighting the use of IBA/PIXE for air particulate matter research in New Zealand (Davy et al., 2002a;b; Trompetter and Markwitz, 2002).

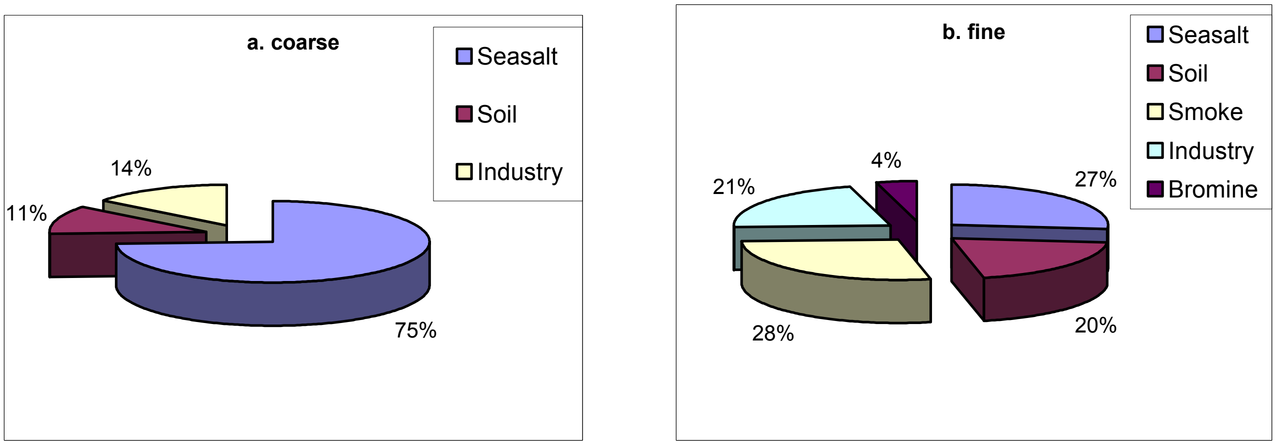

Figure 5: Source apportionment of coarse (a. $PM_{10-2.5}$) and fine (b. $PM_{2.5}$) particulate matter from an urban site in the Wellington region. Source: Trompetter et al. (2002b)

As shown in figure 5a, in Wellington most of the coarse fraction is seasalt, while most of the fine fraction is almost equally distributed to seasalt, soil, smoke, and industry.

More recently, source apportionment using nuclear techniques was performed in Metro–Manila (Santos et al., 2004). Here the coarse particle fraction was determined by a soil-cement mixture and the S-fraction, followed by vehicle emissions and soil tire-wear. In contrast, the fine fraction was determined by biomass burning and oil burning, with smaller fractions of aged salt and black carbon, cf. figure 6. Thiese results give already a clear indication of the importance of the various sources and hints for rational air quality management action, e.g. reduction of biomass and oil burning.

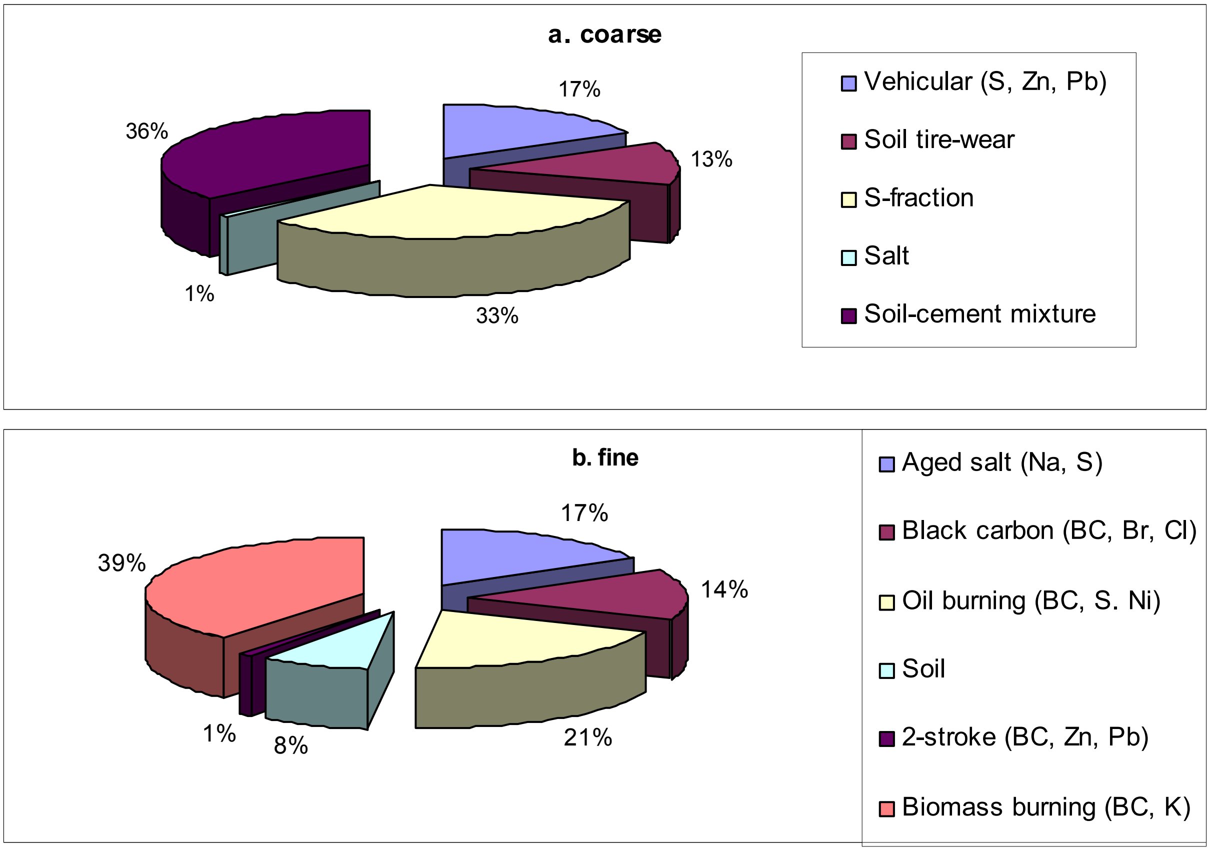

Figure 6: Source apportionment of coarse (a. $PM_{10-2.5}$) and fine (b. $PM_{2.5}$) particulate matter in Metro Manila. Source: Santos et al. (2004).

5. Conclusions

In this paper we described several nuclear analytical techniques that can be used for determination of the elemental composition of coarse and fine particulate matter: neutron activation analysis, X-ray fluorescence, and ion beam analysis. Since the various types of sources of particulate air pollutants are characterized by the elemental composition of the particles, knowledge of the elements in particles allows the identification of the origin of the particles and, thereby, leads to a quantitative apportionment of the existing types of sources. In consequence, most important source types can be identified and decisions can be made on which source types it is most appropriate to reduce emissions. This would constitute a valuable step forward in air quality management, particularly in cases where emissions inventories are not established.

This knowledge can, however, only be obtained at the relatively high costs of the nuclear analytical instrumentation including an air conditioned building. These techniques are, however, applicable not only for solving tasks in air pollution management but can also be used in other fields of environmental management and material testing. Thus the initially necessary high investment may well pay off after a relatively short time. In addition, Asian countries could establish a Regional Centre for Nuclear Analytical Techniques the services of which could be used by several countries.

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