Neutron activation analysis

Neutron activation analysis (NAA) is a nuclear process used for determining the concentrations of elements in a vast amount of materials. NAA relies on excitation by neutrons so that the treated sample emits gamma-rays. It allows the precise identification and quantification of the elements, above all of the trace elements in the sample. NAA has applications in chemistry but also in other research fields, such as geology, archaeology, medicine, environmental monitoring and even in the forensic science.

2.1. Basis principles

The sequence of events occurring during the most common type of nuclear reaction used for NAA, namely the neutron capture or (n, gamma) reaction, is illustrated in [Figure 1](https://www.intechopen.com/chapters/43467#F1). Creation of a compound nucleus forms in an excited state when a neutron interacts with the target nucleus via a non-elastic collision. The excitation energy of the compound nucleus is due to the binding energy of the neutron with the nucleus. The compound nucleus will almost instantaneously de-excite into a more stable configuration through emission of one or more characteristic prompt gamma rays. In many cases, this new configuration yields a radioactive nucleus which also de-excites (or decays) by emission of one or more characteristic delayed gamma rays, but at a much lower rate according to the unique half-life of the radioactive nucleus. Depending upon the particular radioactive species, half-lives can range from fractions of a second to several years.

In principle, therefore, with respect to the time of measurement, NAA falls into two categories: (1) prompt gamma-ray neutron activation analysis (PGNAA), where measurements take place during irradiation, or (2) delayed gamma-ray neutron activation analysis (DGNAA), where the measurements follow radioactive decay. The latter operational mode is more common; thus, when one mentions NAA it is generally assumed that measurement of the delayed gamma rays is intended. About 70% of the elements have properties suitable for measurement by NAA.



**Figure 1.**

Diagram illustrating the process of neutron capture by a target nucleus followed by the emission of gamma rays.

The PGAA technique is generally performed by using a beam of neutrons extracted through a reactor beam port. Fluxes on samples irradiated in beams are in the order of one million times lower than on samples inside a reactor but detectors can be placed very close to the sample compensating for much of the loss in sensitivity due to flux. The PGAA 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 in the samples can be performed by PGAA.

DGNAA (sometimes called conventional NAA) is useful for the vast majority of elements that produce radioactive nuclides. The technique is flexible with respect to time such that the sensitivity for a long-lived radionuclide that suffers from interference by a shorter-lived radionuclide can be improved by waiting for the short-lived radionuclide to decay or quite the contrary, the sensitivity for short-lived isotopes can be improved by reducing the time irradiation to minimize the interference of long-lived isotopes. This selectivity is a key advantage of DGNAA over other analytical methods.

In most cases, the radioactive isotopes decay and emit beta particles accompanied by gamma quanta of characteristic energies, and the radiation can be used both to identify and accurately quantify the elements of the sample. Subsequent to irradiation, the samples can be measured instrumentally by a high resolution semiconductor detector, or for better sensitivity, chemical separations can also be applied to reduce interferences. The qualitative characteristics are: the energy of the emitted gamma quanta (Eγ) and the half life of the nuclide (T½). The quantitative characteristic is: the Iγ intensity, which is the number of gamma quanta of energy Eγ measured per unit time.

The n-gamma reaction is the fundamental reaction for neutron activation analysis. For example, consider the following reaction:

58Fe +1n →59Fe + Beta-+ gamma rays58Fe +1n →59Fe + Beta-+ gamma rays

58Fe is a stable isotope of iron while 59Fe is a radioactive isotope. The gamma rays emitted during the decay of the 59Fe nucleus have energies of 142.4, 1099.2, and 1291.6 KeV, and these gamma ray energies are characteristic for this nuclide (see [figure 2)](https://www.intechopen.com/chapters/43467#F2) [[2](https://www.intechopen.com/chapters/43467#B2)]. The probability of a neutron interacting with a nucleus is a function of the neutron energy. This probability is referred to as the capture cross-section, and each nuclide has its own neutron energy-capture cross-section relationship. For many nuclides, the capture cross-section is greatest for low energy neutrons (referred to as thermal neutrons). Some nuclides have greater capture cross-sections for higher energy neutrons (epithermal neutrons). For routine neutron activation analysis we are generally looking at nuclides that are activated by thermal neutrons.

The most common reaction occurring in NAA is the (n,γ) reaction, but also reactions such as (n,p), (n,α), (n,n′) and (n,2n) are important. The neutron cross section, σ, is a measure for the probability that a reaction will take place, and can be strongly different for different reaction types, elements and energy distributions of the bombarding neutrons. Some nuclei, like 235U are fissionable by neutron capture and the reaction is denoted as (n,f), yielding fission products and fast (highly energetic) neutrons [[1](https://www.intechopen.com/chapters/43467#B1)].

Neutrons are produced via

* Isotopic neutron sources, like 226Ra(Be), 124Sb(Be), 241Am(Be), 252Cf. The neutrons have different energy distributions with a maximum in the order of 3–4 MeV; the total output is typically 105–107 s -1 GBq-1 or, for 252Cf, 2.2 1012 s-1g-1.
* Particle accelerators or neutron generators. The most common types are based on the acceleration of deuterium ions towards a target containing either deuterium or tritium, resulting in the reactions 2H(2H,n)3He and 3H(2H,n)4He, respectively. The first reaction, often denoted as (D,D), yields monoenergetic neutrons of 2.5 MeV and typical outputs in the order of 108–1010 s−1; the second reaction (D,T) results in monoenergetic neutrons of 14.7 MeV and outputs of 109–1011 s−1.
* Nuclear research reactors. The neutron energy distribution depends on design of the reactor and its irradiation facilities. An example of an energy distribution in a light water moderated reactor is given in [Fig. 2](https://www.intechopen.com/chapters/43467#F2).3 from which it can be seen that the major part of the neutrons has a much lower energy distribution that in isotopic sources and neutron generators. The neutron output of research reactors is often quoted as neutron fluence rate in an irradiation facility and varies, depending on reactor design and reactor power, between 1015 and 1018 m-2 s-1.

## Applications

It is hardly possible to provide a complete survey of current NAA applications; however, some trends can be identified [[27](https://www.intechopen.com/chapters/43467#B27)]. At specialized institutions, NAA is widely used for analysis of samples within environmental specimen banking programmes [[28](https://www.intechopen.com/chapters/43467#B28)]. The extensive use of NAA in environmental control and monitoring can be demonstrated by the large number of papers presented at two symposia organized by the IAEA in these fields: "Applications of Isotopes and Radiation in Conservation of the Environment" in 1992 [[29](https://www.intechopen.com/chapters/43467#B29)] and "Harmonization of Health-Related Environmental Measurements Using Nuclear and Isotopic Techniques" in 1996 [[30](https://www.intechopen.com/chapters/43467#B30)]. Similar trends can also be identified from the topics discussed at the regular conference on “Modern Trends in Activation Analysis (MTAA)” and at the symposia on "Nuclear Analytical Methods in the Life Sciences" [[31](https://www.intechopen.com/chapters/43467#B31)-[33](https://www.intechopen.com/chapters/43467#B33)]. Additional sources of recent information on utilizing NAA in selected fields, such as air pollution and environmental analysis, food, forensic science, geological and inorganic materials as well as water analysis can be found in the bi-annual reviews in Analytical Chemistry, for instance cf. Refs [[34](https://www.intechopen.com/chapters/43467#B34)-[42](https://www.intechopen.com/chapters/43467#B42)]. It follows from these reviews that NAA has been applied for determining many elements, usually trace elements, in the following fields and sample types:

1. Archaeology: samples and objects such as amber, bone, ceramics, coins, glasses, jewellery, metal artefacts and sculptures, mortars, paintings, pigments, pottery, raw materials, soils and clays, stone artefacts and sculptures can be easily analyzed by NAA.
2. Biomedicine: the samples and objects that can be analysed include: animal and human tissues activable tracers, bile, blood and blood components, bone, brain cell components and other tissues, breast tissue, cancerous tissues, colon, dialysis fluids, drugs and medicines, eye, faeces, foetus, gallstones, hair, implant corrosion, kidney and kidney stones, liver, lung, medical plants and herbs, milk, mineral availability, muscle, nails, placenta, snake venom, rat tissues (normal and diseased), teeth, dental enamel and dental fillings, thyroid, urine and urinary stones.
3. Environmental: in this domain, related fields concerned by NAA are: aerosols, atmospheric particulates (size fractionated), dust, fossil fuels and their ashes, flue gas, animals, birds, insects, fish, aquatic and marine biota, seaweed, algae, lichens, mosses, plants, trees (leaves, needles, tree bark), household and municipal waste, rain and horizontal precipitations (fog, icing, hoarfrost), soils, sediments and their leachates, sewage sludges, tobacco and tobacco smoke, surface and ground waters, volcanic gases.
4. Forensics: bomb debris, bullet lead, explosives detection, glass fragments, paint, hair, gunshot residue swabs, shotgun pellets.
5. Geology and geochemistry: asbestos, bore hole samples, bulk coals and coal products, coal and oil shale components, crude oils, kerosene, petroleum, cosmo-chemical samples, cosmic dust, lunar samples, coral, diamonds, exploration and geochemistry, meteorites, ocean nodules, rocks, sediments, soils, glacial till, ores and separated minerals.
6. Industrial products: alloys, catalysts, ceramics and refractory materials, coatings, electronic materials, fertilizers, fissile material detection and other safeguard materials, graphite, high purity and high-tech materials, integrated circuit packing materials, online, flow analysis, oil products and solvents, pharmaceutical products, plastics, process control applications, semiconductors, pure silicon and silicon processing, silicon dioxide, NAA irradiation vials, textile dyes, thin metal layers on various substrates.
7. Nutrition: composite diets, foods, food colours, grains, honey, seeds, spices, vegetables, milk and milk formulae, yeast.

 8. Quality assurance: this include analysis of reference materials, certification of element contents and homogeneity testing of mainly biological and environmental reference materials of chemical composition and methods inter-comparisons.