

APPLICATIONS OF NEUTRON ACTIVATION SPECTROSCOPY*

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Since the discovery in 1932, neutrons became a basis of many methods used not only in research, but also in industry and engineering. Among others, the exceptional role in the modern nuclear engineering is played by the neutron activation spectroscopy, based on the interaction of neutron flux with atomic nuclei. In this article, we shortly describe application of this method in medicine and detection of hazardous substances.

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1. Introduction

Neutrons have many properties that make them ideal for certain types of applications, especially concerning imaging and elemental traces detection techniques. As neutral particles, neutrons can deeply penetrate even very dense matter. On the other hand, they interact strongly with nuclei, what is a great advantage over *e.g.* X-rays which interact almost only with electrons in the matter, and thus are “blind” to the type of element.

One of the most important technique being used widely in research and engineering for a long time, is the neutron radiography. As the name implies, a neutron beam penetrates the object to be studied. This beam is attenuated by the sample material depending on the neutron interaction cross sections. The beam is then detected by a two-dimensional imaging device that provides an image representing the macroscopic structure of the

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studied sample [1, 2]. An example of radiographs taken with different methods is presented in Fig. 1, where one can clearly see the differences between X-rays and neutrons. Analogously as for X-rays, a series of n -ray radiographs provides a three-dimensional image of the object inner structure, *i.e.* its tomographic picture. The sensitivity to light elements, especially to hydrogen, makes the n -ray radiography a very valuable alternative to the X-rays. It is used, for example, in studying the flow of oil in automobile transmissions, monitoring complex piping systems and fluid flow, to determine the pyrotechnic product quality and in many other applications [1].

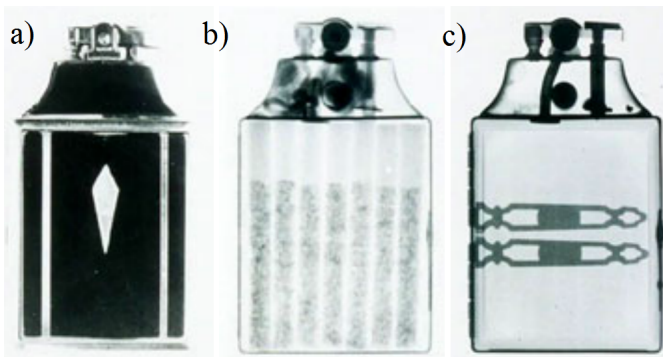


Fig. 1. Comparative radiographs of a cigarette case: (a) photograph, (b) neutron radiography, (c) X-rays radiography. The figure is adapted from [1].

Passing through matter neutrons interact with nuclei in several processes including the elastic and inelastic scattering, neutron capture, fission or particle emission from the nucleus. The inelastic scattering and neutron capture constitute the base of the Neutron Activation Analysis techniques (NAA), which are widely used for the quantitative elemental concentrations determination. These two types of neutron interaction result in the nuclei excitation turning them into radioactive nuclides, which decay emitting gamma rays. Their energies are characteristic for each element, so that the measurement of these gamma rays intensities gives information on the elemental content of the irradiated object. Methods based on NAA have a big application potential since they provide an analysis of a large number of elements simultaneously and non-destructively. Moreover, they have a very low detection limits for many elements. Devices based on NAA are used widely in industry (*e.g.* crude oil and coal deposits identification, water monitoring), medicine and homeland security. The latter two applications will be discussed in more details in next sections of this contribution.

2. Medicine: breast cancer diagnostics

The presently used breast cancer diagnostic methods are based mainly on X-rays imaging (mammography), and have reached almost 98% sensitivity in detecting tumors [3]. However, mammography do not provide sufficiently accurate information which would allow to determine whether the tumor is benign or malicious. Moreover, for confirmation of the diagnosis, one needs invasive biopsy. The other disadvantage is that the radiologists working on the interpretation of the mammography images need a long and expensive training before they are able to set a good diagnosis.

Several studies have demonstrated that breast cancer is associated with changes in the concentration of some elements (*e.g.* calcium, potassium or iron) in the malignant tissue at very early stages¹. These changes often occur much earlier than morphologic changes such as tumors and calcifications. Thus, detection of these changes gives a chance to diagnose of breast cancer much earlier before the tumor grows large enough to be detected by existing imaging techniques [4]. The NAA based techniques are ideal to quantify the concentration of elements of interest in the tissue providing at, the same time, location of region affected by the disorder and diagnosis [4]. Similar method, based on oxygen concentration measurement, is developed by CALSEC [3]. It makes use of the fact that cancerous tumors chemically differ from healthy tissue by the oxygen content. Therefore, any oxygen concentration difference between a tumor and the adjacent healthy tissue indicates that it is malicious. This method is intended to support the conventional methods providing kind of “needleless biopsy”.

Neutron based techniques for cancer diagnosis are at present at an advanced stage of development and will be soon a very useful alternative or supplement of mammography.

3. Homeland security: detection of hazardous substances

In the face of increasing danger of terrorist attacks and still growing trade of illicit drugs, a development of new hazardous substances detection technologies became of a great importance. At present, the detection of concealed contraband is based mainly on the X-rays, vapor detection and sniffer dogs. X-ray scanners suffer from the main disadvantage of having a small cross section interaction with low electron density elements from which organic materials, including most explosives and illicit drugs, are composed. Thus, they are detected mainly through shape recognition, which could be very difficult since the hazardous material can be molded or packed into any

¹ Changes of trace element concentrations in human tissue may be a precursor to malignancy in several other organs such as brain or prostate [4].

form [5]. In fact, up to now the false alarm rates in the airport luggage inspections amount almost to 100%. Also the vapor detection and sniffer dog methods suffer from a high rate of false alarms, especially in the case of people professionally working with explosives or drugs. These methods can be used only for security purposes at airports, in the Civil Service *etc.* In the military application the only devices used, for example, for area demining are metal detectors. In the ground full of metal remains this process became very expensive and time consuming. Moreover, the novel landmines are being made without any metal parts, thus they cannot be detected with those devices.

Neutron-based techniques were considered to be used in the hazardous substances detection for more than forty years, but the first functioning devices were designed and produced at the beginning of 21st century by Maglich [6]. They utilize the fact, that most of the commonly used explosives, drugs or war gases are organic materials. Therefore, they are composed mostly of oxygen, carbon, hydrogen and nitrogen (see Table I). Thus, these

TABLE I

Molecular content of few chosen hazardous substances.

Substance	Stoichiometric formula	Ratio C:H:N:O
Trinitrotoluene (TNT)	$C_7H_5N_3O_6$	1.2 : 0.8 : 0.5 : 1
Hexogen (RDX)	$C_3H_6N_6O_6$	0.5 : 1 : 1 : 1
Nitroglycerine	$C_3H_5N_3O_9$	0.33 : 0.56 : 0.33 : 1
Cocaine	$C_{17}H_{21}NO_4$	4.25 : 5.25 : 0.25 : 1
Heroine	$C_{21}H_{23}NO_5$	4.2 : 4.6 : 0.2 : 1
Amphetamine	$C_9H_{21}NO_4$	4.25 : 5.25 : 0.25 : 1

substances can be unambiguously identified by the determination of the ratio between number of C, H, N and O atoms in a molecule, which can be done non-invasively applying Neutron Activation Analysis techniques. The schematic illustration of one of the possible practical realizations of a device utilizing this method is shown in Fig. 2. The suspected item can be irradiated with a flux of neutrons produced using compact generators based *e.g.* on deuterium–tritium fusion, where deuterons are accelerated to the energy of 0.1 MeV and hit a solid target containing tritium. As a result of the fusion, an alpha particle is created together with the neutron, which is emitted nearly isotropically with a well defined energy equal to about 14.1 MeV. Such energy is sufficient to excite nuclei of carbon ^{12}C (4.43 MeV), oxygen ^{16}O (6.13 MeV) and nitrogen ^{14}N (2.31 MeV and 5.11 MeV) [8]. γ quanta from the de-exciting nuclei are then detected by a germanium detector providing a very good energy resolution. Counting the number of gamma quanta corresponding to a given nuclei provides information about the stoichiome-

try of the examined item. Since the hydrogen nuclei cannot be excited by neutron inelastic scattering, the amount of hydrogen atoms in the sample cannot be examined using this method. Yet, hazardous substances can be discriminated from non-hazardous by the atomic ratio of carbon, oxygen and nitrogen only. There are two major difficulties which have to be solved in this type of detectors. One is an isotropic generation of neutrons which induces unfortunately a large background from irradiation of material surrounding the interrogated object. This noise can be significantly reduced by the requirement of the coincident detection of the alpha particle, which allows for the neutron tagging by registration of the direction of alpha particle [8]. Moreover, germanium detectors are quite expensive and need a cooling system which significantly limit the mobility of the scanner. Thus, there has been done a lot of studies to replace germanium with detector systems based on scintillators.

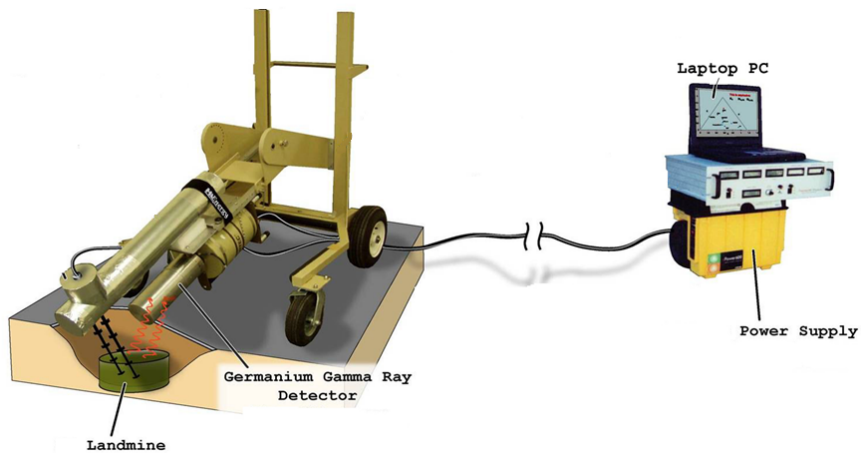


Fig. 2. Illustration of a system for hazardous substances detection based on neutrons. The figure is adapted from [7].

4. Summary

Over the last decade, technologies using fast neutrons have found use in a variety of contexts in the research, industry and engineering. Especially, the Neutron Activation Analysis based techniques were found to be very promising. They may find applications *e.g.* in remote and non-invasive detection of explosives or drugs, as well as in medical diagnostics of cancer tissues. Thus, they could open a new frontiers in homeland security and biomedical sciences.

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