A Brief Overview of Neutron Activation Analyses
Methodology and Applications

M.A.ALI
Nuclear Research Center, Atomic Energy Authority, Egypt.

The primary objective of this talk is to present our new facility for Neutron Activation Analysis to the scientific and industrial societies and show its possibilities. Therefore my talk will handle the following main items:

- An overview of neutron activation analysis,
- The special interest of fast mono-energetic neutrons,
- The NAA method and its sensitivities,
- The Recent scientific and industrial applications using NAA, and
- An illustrating example measured by using our facility is presented

What is NAA?
It is a sensitive analytical technique useful for performing both qualitative and quantitative multi-element analyses in samples.

Worldwide application of NAA is so widespread; it is estimated that approximately several 10,000 samples undergo analysis each year from almost every conceivable field of scientific or technical interest.

Why NAA?
For many elements and applications, NAA
- Offers sensitivities that are sometimes superior to those attainable by other methods, on the order of nano-gram level
- It is accurate and reliable.
- NAA is generally recognized as the "referee method" of choice when new procedures are being developed or when other methods yield results that do not agree.

However, the activation analysis at $E_n=14$ MeV is limited by a few factors:

- Low value of flux, low cross-sections of threshold reactions,
- Short irradiation time due to finite target life,
- Interfering reactions and gamma ray spectral interference.

What is required for NAA?
The basic essentials required to carry out an analysis of samples by NAA are:

- A source of neutrons,
- Suitable instrumentation for detecting gamma rays,
- A detailed knowledge of the reactions that occur when neutrons interact with target nuclei.

Neutrons
Neutrons can be obtained from Reactors, Accelerators, and from Radio-isotopic neutron emitters.

For NAA, neutrons from accelerators (due to nuclear reactions) and from nuclear reactors (due uranium fission) offer the highest available sensitivities for most elements.
Accelerators provide fast mono-energetic neutrons. Fast neutrons contribute very little to the (n, \gamma) reactions, but instead induced nuclear reactions where the ejection of one or more nuclear particles (n, p), (n, n'), and (n, 2n) - are prevalent.

1- Neutrons from accelerators.

Many nuclear reactions can produce fast mono-energetic neutrons. The target structure, which contains or supports the active part of the target and usually stops the unused portion of the beam, may provide neutrons of undesired energy (back-ground). Inter-comparison of various sources should help in selecting the most suitable neutron source for a given experimental situation.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Break up reaction</th>
<th>Break up threshold (MeV)</th>
<th>Neutron energy range (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^3\text{He} ) (d, n) ( ^3\text{He} )</td>
<td>( D ) (d, np) ( D )</td>
<td>4.45</td>
<td>1.65 --- 7.75</td>
</tr>
<tr>
<td>( ^3\text{He} ) (d, n) ( ^3\text{He} )</td>
<td>( T ) (d, np) ( T ) ( T ) (d, 2n) ( ^3\text{He} )</td>
<td>3.71</td>
<td>11.75 --- 20.5</td>
</tr>
<tr>
<td>( ^3\text{He} ) (p, np) ( ^3\text{He} )</td>
<td>( T ) (p, np) ( D )</td>
<td>8.35</td>
<td>0.3 --- 7.6</td>
</tr>
<tr>
<td>( ^7\text{Li} ) (p, n) ( ^7\text{Be} )</td>
<td>( ^7\text{Li} ) (p, n) ( ^7\text{Be} )</td>
<td>2.37</td>
<td>0.12 --- 0.6</td>
</tr>
</tbody>
</table>

Some disadvantageous of the d-D and d-T reactions are:
- After a long use of the same target, a self-target build up in the beam stop is noticed. This gives additional low energy background neutrons.
- The differential cross section of the d-D reaction has a much stronger angular dependence.

Ranges of applicability of the “big-4” reactions are shown in Table 1. Because of the deuteron break up in the d-D and d-T reactions above 4 MeV, there is a gap in the energy range of mono-energetic neutrons from 8 to 12 MeV.

II- Neutrons from reactors.

Different types of reactors and different positions within a reactor can vary considerably with regard to neutron energy distributions and fluxes due to the materials used to moderate the primary fission neutrons. Most neutron energy distributions are quite broad and consist of three principal components:
- Thermal, Epi-thermal, and Fast.

The thermal neutron component consists of low-energy neutrons (energies below 0.5 eV) in thermal equilibrium with atoms in the reactor's moderator.

In most reactor irradiation positions, 90-95% of the neutrons that bombard a sample are thermal neutrons. In general, a one-megawatt reactor has a peak thermal neutron flux of approximately 1E13 neutrons per square centimeter per second.

The epi-thermal neutron component consists of neutrons (energies from 0.5 eV to about 0.5 MeV) which have been only partially moderated. In a typical unshielded reactor irradiation position, the epi-thermal neutron flux represents about 2% of the total neutron flux.

Both thermal and epi-thermal neutrons induce (n, \gamma) reactions on target nuclei.

An NAA technique that employs only epi-thermal neutrons to induce (n, \gamma) reactions by irradiating the samples being analyzed inside either cadmium or boron shields is called epi-thermal neutron activation analysis (ENAA).

The fast neutron component of the neutron spectrum (energies above 0.5 MeV) consists of the primary fission yielding neutrons which still have much of their original energy following
fission. In a typical reactor irradiation position, about 5% of the total flux consist of fast neutrons.

An NAA technique that employs nuclear reactions induced by fast neutrons is called fast neutron activation analyses (FNAA).

The \((n, \gamma)\) reactions of thermal neutrons and the \((n, xy)\) reaction of fast neutrons are quite complementary to each other. Whereas the \((n, \gamma)\) cross-section is very low for most light elements, e.g. Li, Be, B, C, O, Na, Mg, Al, with notable exception of hydrogen, the \((n, xy)\) cross-section for these elements is quite respectable. Furthermore, the yield and the specificity of gamma rays from \((n, xy)\) are very high.

**Neutron Activation Process**

Neutron activation analysis was discovered in 1936 when Hevesy and Levi \(^{(2)}\) found that samples containing certain rare earth elements became highly radioactive after exposure to a source of neutrons.

From this observation, they quickly recognized the potential of employing nuclear reactions on samples followed by measurement of the induced radioactivity to facilitate both qualitative and quantitative identification of major, minor, and trace elements present in the samples.

The sequence of events occurring during the most common type of nuclear reaction used for NAA; namely the neutron capture is illustrated in the following figure:

![Neutron Capture Diagram](image)

**Figure 1.** A diagram illustrates the process of neutron capture by a target nucleus followed by the emission of gamma rays.

When a neutron interacts with the target nucleus via a non-elastic collision, a compound nucleus forms in an excited state. 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 decays by emission of one or more characteristic delayed gamma rays, but at a much slower rate according to the unique half-life of the radioactive nucleus. Depending upon the particular radioactive species, half-lives can range from a fraction 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, it is generally assumed that NAA means the measurement of the delayed gamma rays. About 70% of the elements have properties suitable for measurement by NAA.

1- Prompt vs. Delayed NAA

The PGNAA technique is generally performed by using a beam of neutrons extracted through a reactor beam port. Fluxes on samples irradiated in beams are on 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. Experiments to measure prompt gamma rays induced by fast neutrons from neutron generators can be also carried out. In such a case, a special shielding design for the experiment set up and a special care of the gamma detectors are a must.

The PGNAA 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 DGNAA; elements that produce only stable isotopes; or elements with weak decay gamma-ray intensities.

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. This selectivity is a key advantage of DGNAA over other analytical methods.

2- Instrumental vs. Radiochemical NAA

With the use of automated sample handling, gamma-ray measurement with solid-state detectors, and computerized data processing it 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.

If chemical separations are done to samples after irradiation to remove interference or to concentrate the radionuclide of interest, the technique is called radiochemical neutron activation analysis (RNAA). The latter technique is performed infrequently due to its high labor cost.

II- The NAA Method

It is very simple, we know that the specific activity, i.e. the activity per unit target mass (m) - in disintegration per second per gram is written as:

\[ R(t) = \frac{A(t)}{m} = 6.02 \times 10^{-6} \frac{\sigma \varphi t_0}{M} (1 - e^{-\lambda t}) \]

Where \( \sigma \) is the cross section of the reaction and is given in mb, the atomic weight of element M is in grams. The target isotopic abundance \( f \) is in percent, and \( \varphi \) is the reaction flux, and \( \lambda \) is the decay constant of the formed radionuclides.

The count rate in the full energy gamma-ray peak, at a time \( t_d \) after an irradiation of an element \( j \) placed in a neutron flux \( \varphi \) for an irradiation time \( t_i \) is given by:

\[ A(t_d) = b \varphi \frac{m_j f_j}{M_j} (1 - e^{-\lambda t_d}) e^{-\mu t_d} \]

Where \( b \), \( \varepsilon \), \( m_j \), \( L \), and \( M_j \) are the gamma-ray branching ratio, the detecting efficiency, the mass of element \( j \), Avogadro's number, and the atomic weight of element \( j \), and

The number of counts \( D \), collected during the time interval \( t_c \) is given by:

\[ D = \frac{A(t_d)}{\lambda} (1 - e^{-\mu t_c}) \]
II- NAA Sensitivities

As we know, while the \((n, \gamma)\) cross-section is very low for most light elements, the \((n, x\gamma)\) cross-section for these elements is quite respectable.

Table (2): presents the total cross section\(^{(3)}\) of production of gamma rays at \(E_n= 14\) MeV and at thermal neutron energies for some elements.

<table>
<thead>
<tr>
<th>Element</th>
<th>(E_n= 14) MeV (mb)</th>
<th>(E_{th}) (mb)</th>
<th>Element</th>
<th>(E_n= 14) MeV (mb)</th>
<th>(E_{th}) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>330</td>
<td>Cu</td>
<td>5985</td>
<td>4500</td>
<td></td>
</tr>
<tr>
<td>Li</td>
<td>3.6</td>
<td>Zn</td>
<td>5570</td>
<td>760</td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td>9</td>
<td>Zr</td>
<td>5830</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>(160)</td>
<td>100</td>
<td>Mo</td>
<td>6800</td>
<td>2550</td>
</tr>
<tr>
<td>C</td>
<td>230</td>
<td>3.5</td>
<td>Cd</td>
<td>7192</td>
<td>2450</td>
</tr>
<tr>
<td>N</td>
<td>314</td>
<td>75</td>
<td>In</td>
<td>6815</td>
<td>194</td>
</tr>
<tr>
<td>O</td>
<td>474</td>
<td>.2</td>
<td>Sn</td>
<td>6480</td>
<td>626</td>
</tr>
<tr>
<td>Na</td>
<td>14866</td>
<td>530</td>
<td>Ta</td>
<td>9000</td>
<td>20500</td>
</tr>
<tr>
<td>Mg</td>
<td>1445</td>
<td>51</td>
<td>W</td>
<td>10400</td>
<td>18400</td>
</tr>
<tr>
<td>Al</td>
<td>1832</td>
<td>231</td>
<td>Hg</td>
<td>9400</td>
<td>372</td>
</tr>
<tr>
<td>Si</td>
<td>166620</td>
<td>177</td>
<td>Pb</td>
<td>6500</td>
<td>171</td>
</tr>
<tr>
<td>P</td>
<td>2515</td>
<td>172</td>
<td>Bi</td>
<td>11680</td>
<td>34</td>
</tr>
<tr>
<td>S</td>
<td>2419</td>
<td>530</td>
<td>(^{235})U</td>
<td>20632</td>
<td>98300</td>
</tr>
<tr>
<td>Ti</td>
<td>4010</td>
<td>7840</td>
<td>(^{239})U</td>
<td>10546</td>
<td>22000</td>
</tr>
<tr>
<td>Fe</td>
<td>4490</td>
<td>2590</td>
<td>(^{239})Pu</td>
<td>23150</td>
<td>269</td>
</tr>
</tbody>
</table>

The sensitivities for NAA are dependent upon the irradiation parameters (i.e., neutron flux, irradiation and decay times), measurement conditions (i.e., measurement time, and detector efficiency); nuclear parameters of the elements being measured (i.e., isotope abundance, neutron cross-section, half-life, and gamma-ray abundance).

The following tables give the detection limits for 14 MeV and 3 MeV fast neutrons produced by neutron generators.

Table 3: gives the detection limits\(^{(4)}\) for thermal neutrons produced by a 14 MeV neutron of output \(10^{11}\) n. s\(^{-1}\).

<table>
<thead>
<tr>
<th>Limit of detection (mg)</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001 -- 0.0003</td>
<td>Dy</td>
</tr>
<tr>
<td>0.004 -- 0.009</td>
<td>Mn, Rh, Ag, Hf</td>
</tr>
<tr>
<td>0.01 -- 0.03</td>
<td>Sc, V, Kr, In, Eu</td>
</tr>
<tr>
<td>0.04 -- 0.09</td>
<td>Cs, Sm, Ho, Lu, Re, Ir, Au</td>
</tr>
<tr>
<td>0.1 -- 0.3</td>
<td>Al, I, Ba</td>
</tr>
<tr>
<td>0.4 -- 0.9</td>
<td>Na, Cu, Ga, As, Br, Sr, Y, Nb, La, W, Os, U</td>
</tr>
<tr>
<td>1 -- 3</td>
<td>Co, Ge, Ru, Pd, Sb, Te, Xe, Nd, Er, Yb, Pt, Hg</td>
</tr>
<tr>
<td>4 -- 9</td>
<td>Ar, Mg, Mo, Cd, Pr, Gd, Ta</td>
</tr>
<tr>
<td>10 -- 30</td>
<td>F, Cl, Ti, Zn, Se, Sn, Ce, Th</td>
</tr>
<tr>
<td>40 -- 90</td>
<td>Ne, K, Ca, Ni, Rb, Tm</td>
</tr>
</tbody>
</table>

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Table 4: The calculated detection limits\(^{(4)}\) for 14 MeV with \(\varphi = 10^9\) neutrons cm\(^{-2}\)s\(^{-1}\).

<table>
<thead>
<tr>
<th>Limit of detection (mg)</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001 - 0.003</td>
<td>Pr</td>
</tr>
<tr>
<td>0.004 - 0.009</td>
<td>Cu, Ga, Ba, Ce</td>
</tr>
<tr>
<td>0.01 - 0.03</td>
<td>Si, P, Sc, Rh, Zr, Pd</td>
</tr>
<tr>
<td>0.04 - 0.09</td>
<td>Al, V, Cr, Ag, Cd, Sb, Hf, Pb</td>
</tr>
<tr>
<td>0.1 - 0.3</td>
<td>N, F, Mg, Mn, Fe, Zn, Ge, Mo, Sn, Te, Sm</td>
</tr>
<tr>
<td>0.4 - 3</td>
<td>Na, k, Co, Sr, Nb, Cs, Ta</td>
</tr>
<tr>
<td>1 - 3</td>
<td>O, Ti, As, In, La, Nd, Eu, Gd, Er, Pt</td>
</tr>
<tr>
<td>4 - 9</td>
<td>Ni, I</td>
</tr>
<tr>
<td>10 - 30</td>
<td>Cl, Ru, Tb, Dy</td>
</tr>
<tr>
<td>40 - 90</td>
<td>S, Ca</td>
</tr>
</tbody>
</table>

Table 5: Sensitivities\(^{(5)}\) for 3 MeV neutron activation analysis with \(\varphi = 10^6\) n.cm\(^{-2}\)s\(^{-1}\).

<table>
<thead>
<tr>
<th>Counts /g</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - (10^2)</td>
<td>Mg, Cl, Co, Ni, Nb</td>
</tr>
<tr>
<td>(10^2) - 3(x10^2)</td>
<td>F, Na, Ti, Zr, La, Pb</td>
</tr>
<tr>
<td>(3\times10^3) - (10^4)</td>
<td>Al, Cu, Zn, Ru, Sb, Hf</td>
</tr>
<tr>
<td>(10^3) - 2(x10^4)</td>
<td>G, As</td>
</tr>
<tr>
<td>2(x10^4) - 5(x10^4)</td>
<td>V, Br, Rb, Mo, Pd, Sn, Gd, Ir, Pt</td>
</tr>
<tr>
<td>5(x10^4) - 2(x10^4)</td>
<td>Mn, Se, Sr, Y, I, Cs</td>
</tr>
<tr>
<td>2(x10^4) - 6(x10^4)</td>
<td>In, Ba</td>
</tr>
<tr>
<td>&gt; 6(x10^4)</td>
<td>Ag, W, Au</td>
</tr>
</tbody>
</table>

The thermal (TNAA) and resonance (RNAA) neutron activation analysis and the captured gamma's are favored over fast neutrons for the elements indicated in the following table:

Table 6 Recommended\(^{(6)}\) methods for elemental analysis.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal NAA</td>
<td>Dy, Eu, In, Mn, Lu, Au, V</td>
</tr>
<tr>
<td>Resonance NAA</td>
<td>U, Th, Rb, Sr, Mo, Sb, Cs, Ba, Ta, Tb</td>
</tr>
<tr>
<td>Capture</td>
<td>H, Be, B, N, O, S, Ni, Cd, Gd, Eu</td>
</tr>
</tbody>
</table>

Table 7 gives \(^{(7)}\) the estimated detection limits for INAA using decays gamma rays assuming irradiation in a reactor neutron flux of \(1x10^{13}\) n cm\(^{-2}\)s\(^{-1}\).

<table>
<thead>
<tr>
<th>Sensitivity (picograms)</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dy, Eu</td>
</tr>
<tr>
<td>1 - 10</td>
<td>In, Lu, Mn</td>
</tr>
<tr>
<td>10 - 100</td>
<td>Au, Ho, Ir, Re, Sm, W</td>
</tr>
<tr>
<td>100 - 1E3</td>
<td>Ag, Ar, As, Br, Cl, Co, Cs, Cu, Er, Ga, Hf, I, La, Sb, Sc, Se, Ta, Tb, Th, Tm, U, V, Yb</td>
</tr>
<tr>
<td>1E3 - 1E4</td>
<td>Al, Ba, Cd, Ce, Cr, Hg, Kr, Gd, Ge, Mo, Na, Nd, Ni, Os, Pd, Rb, Rh, Ru, Sr, Te, Zn, Zr</td>
</tr>
<tr>
<td>1E4 - 1E5</td>
<td>Bi, Ca, K, Mg, P, Pt, Si, Sn, Ti, Tl, Xe, Y</td>
</tr>
<tr>
<td>1E5 - 1E6</td>
<td>F, Fe, Nb, Ne</td>
</tr>
<tr>
<td>1E7</td>
<td>Pb, S</td>
</tr>
</tbody>
</table>
Applications

The following is a very brief presentation of some 14-MeV NAA applications in some selected scientific and technical activities.

Csikai (8), and Alfassi and Parry (9), and the references listed there in, review the details of these and many other applications.

1- Archaeology

The use of neutron activation analysis to characterize archaeological specimens (e.g., pottery, obsidian, basalt and limestone) and to relate the artifacts to sources through their chemical signatures is a well-established application of the method.

Over the past decade, large databases of chemical ‘fingerprints’ for clays, obsidian, and basalt have been accumulated through analysis of approximately thirty elements in each of more than 32,000 specimens. The combination of this database with powerful multivariate statistical and other methods allows many archaeological materials to be sourced with a high degree of confidence. The sourcing information can help archaeologists reconstruct the habits of prehistoric peoples.

For example, the "fingerprinting" of obsidian artifacts by NAA is a nearly 100 percent successful method for determining prehistoric trade routes since sources of obsidian are easily differentiated from one another through their chemical compositions.

The determination of Si, Al, Mg, and Fe as major components in ancient pottery and many other elements is required in archaeological researches.

2- Metallurgy

The physical and mechanical properties of metals and alloys are influenced significantly by the presence of elements as alloying admixtures. The application of FNAA provides a fast and precise determination of the major and minor constituents.

The most common application of 14-MeV NAA is the determination of O, mainly in metals and especially in steels. The reason for this is that conventional methods (e.g., vacuum fusion and mercury amalgam) are difficult to apply to the determination of low level O contents. Small amounts of O can exert considerable influence on the physical, mechanical, and chemical properties of the substances. In metals, O, cause brittleness and in organic substances, it may give rise to corrosion phenomena. Because steels are usually oxides, 14-MeV NAA is suitable for the detection of non-metallic inclusion in them. It has been shown that O contents in metals of about 1 ug can be detected by NAA. Lauff et al. (11) have developed a differential method for the analysis of O in the presence of F. The sensitivity for the F determination is 0.4 mg in a 10-g sample; for O, it is 0.04 mg.

The alloy Al-Al₂O₃ is extensively used as cladding material for nuclear reactor fuel elements. The results of O determination with various methods show considerable deviation. According to Brmlitt (12), the accuracy of 14-MeV NAA is within ±3%; for the quantitative determination of Al₂O₃ in Al alloys. It attains the accuracy of the wet chemical method, but with a time reduction of more than 90%.

Recently, Beurton (13) has determined the concentration of three nonmetallic elements N, O, and F in Al-Zn and Al-Cu alloys in the range 0.5 to 10 μg/g with 14-MeV NAA.

In addition to O, 14-MeV NAA is applied in the determination of Si, which is difficult to determine by wet chemistry. The favorable property of the reaction ²⁸Si(n,p)²⁹Al permits a rapid, nondestructive, and sensitive determination of Si in a wide variety of matrices, (e.g., cast iron, Al, Si-compounds, rocks, minerals...etc.). The 14-MeV NAA has many advantages in the determination of SiO₂ in Fe and steel-making slag’s as compared to the other chemical and physical methods. The limit of detection of SiO₂ in this matrices was found to be 0.07%.

For the determination of Zr, Al, and Si in ignition rods used to ignite oil-engines, 14-MeV NAA was used (15).
Therefore, FNAA is a useful method in the development of many metallurgical process and applications.

3- Chemistry

Neutron generators have been employed in the analysis of various chemical products in industry. The primary light sensitivity of the photo-emulsion depends on the composition of the silver halide components. Therefore, an accurate and rapid method of analysis for the halides in this matrix is profitable.

Low Concentrations of impurities in explosive propellants can influence safety in handling. As the process and quality control require the testing of large number of samples, wet chemical methods are not ideal. Therefore, purity control through measuring the total N content by 14 MeV NAA by means of the $^{14}\text{N}(n,2n)^{13}\text{N}$ reaction is attractive. Rison et al.\(^{(16)}\) reported for 50 mg RDX samples an absolute error of 0.3% in N content determination.

14 MeV NAA has been used for the determination of Na and P in organic compounds\(^{(17)}\). The advantage of this method in addition to its rapidity is that does not exclude the possibility of further investigation of the sample. The sensitivity of the method is $6 \times 10^{-4}$ g for Na and $3.5 \times 10^{-5}$ g for P in organic-phosphorous compounds. The time required for determination is about 5 min.

A method for simultaneous determination of Ba, P and O in oil additive based on 14 MeV NAA has been developed by Kliment et. al.\(^{(18)}\).

14 MeV NAA has been used to study the properties of the fire-retardant insulators. The concentration of Sb and Cl in several synthetic rubbers were determined by Bild\(^{(19)}\) using the $^{35}\text{Cl}(n,p)$ and $^{123}\text{Sb}(n,2n)$ reactions. The detection limits were 0.5 and 0.02 wt % respectively. The 14 MeV NAA can contribute also to the solving of problems in hot atom chemistry\(^{(20)}\).

The determination of O, Si, Al, Ti, N, Ba, P, Zn, Y, Cr, Fe, Dy, Eu, and Zr in oxides, glasses, refractoriness, circuit boards, and thin films is required by electronic industry.

4- Biology

There are about 40 elements that constitute the organisms of the biosphere\(^{(21)}\). The determination of trace element concentration in human material can provide information on normal or pathological conditions. Also, a change in the concentration of microelements in plants results in a change in the main constituents and influences the biological value of vegetable nutritive materials.

Various elements (O, N, F, Na, Mg, Al, Si, P, S, Cl, Ca, Ti and Fe) have been determined in biological materials with 14-MeV neutrons. Crambes et al.\(^{(21)}\) has performed the elemental analysis of proteins and amino acids for N, O, S, and P. It was found that at a flux of $10^{9}$ n cm\(^{-2}\)s\(^{-1}\), the minimum amount of amino or proteins needed to achieve a 5% precision in their determination is 10g. The results of 14-MeV NAA are in good agreement with those obtained by chemical methods. The investigation proved the applicability of activation analysis for proteins without any measurable effect of radiation damage.

The 14-MeV NAA are widely used for the determination of protein contents in plants and corn meals via the $^{14}\text{N}(n,2n)^{13}\text{N}$ reaction, since proteins contain a well-known amount of N. For example, the Soya bean contains 30 to 40% crude proteins, 15 to 20% oils, and 30% carbohydrates. The main advantage of the nondestructive 14-MeV NAA is that the selection of seed corn with high protein content is possible, and it can be used to obtain new sources of protein.

In diseases of bone, the Ca and P content can change significantly. Hyvönen-Dbek et. al.\(^{(22)}\) have described a method based on 14-MeV NAA for in vitro measurement of the P content of bones. The Ca/P ratio for compact bone was also determined and the suitability of the $^{31}\text{P}(n,a)^{28}\text{Al}$ reaction induced by 14 MeV neutrons for studying bone mineral composition in vitro has been discussed\(^{(23)}\). FNAA was also used to study the chemical composition of fossil bones by systematic measurements on a large number of samples.

Anderson et al.\(^{(24)}\) introduced the in vivo activation analysis method to estimate the whole body content of sodium by whole body exposure to 14 MeV neutrons. This technique allows the
elements in the living human body to be determined more easily than by other methods. There are, however, two difficulties associated with the in vivo analysis: the calibration and the radiation hazards.

NAA was used to provide accurate in vivo measurement of relative changes in whole body Ca and in regional Ca and P contents. The blood flow in an organ can be measured in vivo by irradiating with short pulses of 14 MeV neutrons. Some general and particular aspects of in vivo NAA are discussed in reference 26.

Ehmann et. al. (27) have determined the contents of trace elements in human brain tissue to find correlation between the concentration anomaly and certain diseases and age. The N and P contents are determined by 14-MeV NAA.

Cercasov and Heller (28) investigated the suitability of using Ce and Sm as markers to determine the rates of passage of different hay particles through the digestive tract of animals.

Further details on the use of neutron generators in life science can be found in Reference 29.

5- Biochemistry

Over the last several years there has been a growing interest in the use of in-situ radio-tracers to test new pharmaceuticals and dosage forms being developed for commercial distribution. This is very important for pharmaceutical companies, universities, and research centers. The in-situ radio-tracers are produced through a carefully designed irradiation and used in laboratory experiments. These methodologies offer significant advantages in the evaluation of encapsulations, time release, clearance and the distribution of the pharmaceutical in animal and human models.

High-specific activity radiotracers, produced by neutron activation, have been used with great success to study biochemical processes in the small animal model. For example, selenium-75, having a specific activity of 1000 Ci/g has been used to advance the discovery of dependent enzymes and other biologically important proteins.

The clinical determination of fat mal-absorption is under-utilized largely due to its cost, difficulty and long time requirement. By using the Dy tracer to establish the meal fraction sampled, fat absorption can be measured in a single stool sample rather than the 72 hour collections that must be made and analyzed under the currently accepted practice. These grants cover the costs of clinical trials and the analyses needed to evaluate the methodology. If successful, this method of measuring fat absorption will be offered to hospitals and clinics in kit form.

6- Environmental Restoration

Analytical technique must be developed and employed to characterize a wide variety of sample matrices (e.g. similar to nuclear weapons waste) which may contain significant concentrations of actinide and rare earth elements. NAA is an important technique in this effort. For example, epi-thermal NAA has been shown to be a powerful tool in the characterization of uranium over a wide range of concentrations (sub-ppm to several percent) in samples that may also have a rare earth content of 10 percent or greater.

The equipment and procedures employed to determine the major (O, Si) and some trace elements (Fe, Al, Mg) present in oceanographic samples using 14-MeV NAA are described by Kuykendall (31).

14-MeV NAA has been applied in the study of air and water pollution. F and Si in air dust and Br in river water have been determined. From the investigation of van Grieken and Dams, it appears that Si determinations in urban and industrial aerosols are easily feasible with FNAA.

Fresh-water ecosystems in California have been grossly contaminated with selenium as a result of irrigation run-off from heavily used agricultural areas. The effect has been observed throughout most of the food chain. The objective of that study was to evaluate the extent of the
contamination and evaluate methodologies that might be efficacious in the reduction of selenium in these ecosystems.

In the 10 years between 1948 and 1958 uranium ore mining in the United States expanded from a cumulative total of 38000 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 in the contamination of hundreds of 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 waste materials such as ore tailings, and processing residues. In other cases the tailings or wastes have remained exposed and hence have been further distributed by wind and erosion. ENAA has been developed as a methodology suitable for automation by which contaminated ore-processing sites can be characterized and their restoration monitored.

There are several fast, nondestructive nuclear methods, which in principle are applicable for the determination of U and Th in rocks and minerals. The advantages and disadvantages of each method depend on the actual experimental conditions (age, type of rocks, composition of the matrix, penetrability of the soil, etc.). The following neutron methods could complement conventional procedures:

1. Resonance NAA by detection of 74.7-keV line from $^{239}$U.
2. Detection of fragments from thermal and fast neutron fission of $^{235}$U and $^{235,238}$U + $^{232}$Th, respectively, using the Cd difference method.
3. Detection of delayed neutrons from thermal and fast neutron-induced fission of $^{235}$U and $^{235,238}$U + $^{232}$Th, respectively.
4. Measurement of the time distribution in rocks following a burst of fast neutrons.

7 - On-line Activation Analysis

On-stream elemental analysis is a further development of methods for sample analysis. Such methods are important for continues industrial process because they enable the operator to act quickly to achieve the optimum yield and quality\(^{(34)}\). In addition to other physical and chemical methods, NAA—can also be used for continuous analysis. Th most frequent fields of application are the on-stream analysis of solutions and the analysis of solid substances on conveyor belts. Continuous neutron activation analysis (CNAA) has been reviewed by Kliment and Tölgyessy\(^{(35)}\). The activity measured by the detector depends on the nuclear properties of elements in the sample, the neutron flux, the flow rate, the layer thickness, the geometry of the arrangement, etc. The variation in activity as a function of layer thickness is week above 10 cm where saturation is reached.

Kartashev and Shtan\(^{(36)}\) have given the sensitivity of CNAA for thermal and fast neutrons. The detection limit is given in Table 8 for a neutron output of $5 \times 10^7$ n/s and a measuring time of 1 h, detecting the gamma’s ith a 3”x3” Nal (Tl) crystal.

<table>
<thead>
<tr>
<th>Limit mg/l</th>
<th>Thermal neutrons</th>
<th>Fast neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 1</td>
<td>Sc, In, Eu, Rh, Mn, Dy, Hf, Sm, Ag, V, I, Br, Ho, Lu, Au</td>
<td>P, Pt, Br, Sb</td>
</tr>
<tr>
<td>1 - 10</td>
<td>W, Se, Co, Cu</td>
<td>Ce, Si, Cu, Cr, Zr</td>
</tr>
<tr>
<td>10 - 100</td>
<td>Y, Ga, Al, Cl</td>
<td>F</td>
</tr>
<tr>
<td>100 - 1000</td>
<td>Ge, Pd, Ir, Te, Vb, As, Mg, Ba, Re, Nb, La</td>
<td>I, Mg, Mn, Zn, Cl, Na, Ge, Ir, Ag, V</td>
</tr>
</tbody>
</table>

Martin et al\(^{(37)}\) has carried out extensive investigation of the determination of various elements in coal by means of CNAA. Its C, O, Al, and Si content check the quality of the coal under industrial conditions. CNAA can be used to determine Al, and Si in cement and sand.

80
**Results and Discussions**

The instrumentation used to measure gamma rays from radioactive samples generally consists of a semiconductor detector, associated electronics, and a computer-based, multi-channel analyzer (MCA/computer). The two most important performance characteristics of detectors are resolution and efficiency. Other characteristics to consider are peak shape, peak-to-Compton ratio, crystal dimensions or shape.

The detector's resolution is a measure of its ability to separate closely spaced peaks in a spectrum. For most NAA applications, a detector with 1.0-keV resolution or below at 122-keV and 1.8-keV or below at 1332 keV is sufficient.

Detector efficiency depends on the energy of the measured radiation, the solid angle between sample and detector crystal, and the active volume of the crystal. For most NAA applications, a detector of 15-30 percent efficiency is adequate.

Hyper-pure or intrinsic germanium (HPGe) detectors are commonly used in most NAA labs. The most suitable detectors for NAA are GMX detectors equipped with transistor-reset preamplifier. Although detectors come in many different designs and sizes, the most common type of detector is the coaxial detector, which is useful over the range from about 60-keV to 3.0-MeV.

As an illustrating example, we present the following measurements:

Figures 3 (a,b) and 4 (a,b) are the gamma-ray spectra for two different lamp crystals. Samples are irradiated for 2 minutes, decayed for some minutes (listed in the figures), and measured by an HPGe detector. The figures show gamma-ray spectra for the short and medium lived elements in the samples.

From these measurements, we can by using good software determine most of the elements in these samples qualitatively and quantitatively.

**Conclusions**

The production of gamma rays resulting from neutron interaction in matter often provides invaluable information on the elemental composition. If the energy of the neutrons is very low, (thermal), radiative capture \((n,\gamma)\) yields a wealth of very specific and sharp gamma rays which form the basis for the prompt neutron gamma activation analysis.

If the energy of the neutrons is high, (fast), such as those generated by small accelerators, different but also specific gamma rays are produced. In this way, not only can inelastic scattering be used for investigations, but also the various neutron reactions- \((n,p)\), \((n,\alpha)\), and \((n,2n)\)- that produce isotopes with short half-lives. Therefore, the use of neutron generators had made a significant contribution in the development of activation methods in different fields in science, life sciences and industry.

The method and the analysis techniques are well known and established. In general, the results of the NAA are in good agreement with the other nuclear and chemical methods. Wide and disperse applications in many different domains in science and life have been done can be carried out here using our facility. To solve any problem, we have to have the suitable reference standards and suitable software that analyses the elements under question.

We are ready now to offer our service to study and help in solving specific problems in science and life using neutron generator facility.
References:
1 - J W Meadows and D C Smith IAEA INDC(NDS)- 114 GT, IAEA, Vienna, 1980
3 - M D Glascock Tables for Neutron Activation Analysis, Missouri University Research Reactor Center, Columbus, 1996
4 - V.P Guinn Proc Conf Use of Small Accelerators for teaching and research, CONF680411, Oak Ridge, Tenn., 1968
6 - J Csikai,4th International Conference on Applications on Nuclear Techniques, Crete, Greece, 1994
12 - E T Bramlett Determination of total Oxygen in Al-Al₂O₃ alloys by fast neutron activation analysis, ALCE-74 U S Atomic Commission Oak Ridge, Tenn 1967
13 - G. Beurton J. Radioanal. Chem. 77, 123, 1983
16 - M H. Rison, W H. Barber, P E. Wilkniss Radiochim Acta, 7, 196, 1967
19 - W R Bild J Radioanal Chem . 72(1-2), 23, 1982
24 - J Anderson et al NAA in man in vivo, a neww technique in medical investigation, Lancet, 1, 1201. 1964
31 - W E Kuykendall, B W Hoffmann, and R E Vainerdi, in Proc 2nd Oak Ridge Conf. Tenn , 221, 1970
34 - S Szegedi, and T Scharbert IAEA training Course Vienna, 130, 1982.