Neutron activation of deferred gamma rays: steps to determine the usefulness of this technique in analyzing elements of a mineral sample

M A Rey-Ronco¹, T Alonso-Sánchez² and M P Castro-García²

¹Departamento de Energía, Universidad de Oviedo, Oviedo 33004, Spain.
²Departamento de Explotación y Prospección de Minas, Universidad de Oviedo, Oviedo 33004, Spain.

E-mail: castromaria@uniovi.es

Abstract. This work shows the steps to be taken in order to determine the theoretical feasibility of applying neutron activation analysis in determining a given element in a mineral sample. A practical case involving the study of the feasibility of this technique in the determination of SiO₂ in a sample of coal has been studied. Databases to obtain information necessary for completion of the feasibility study are shown.

1. Basis of neutron activation analysis
Neutron activation analysis (NAA) is a useful analytical technique to realize quantitative and qualitative analysis to determine large number of elements and involves the irradiation of a nucleus with neutrons to produce radionuclides [1-2]. This technique has been used from 1936 [3]. The number of radionuclides produced will depend on the number of target nuclei, the number of neutrons and on the factor called the cross section which defines the probability of activation occurring. If the activation product is radioactive, it will decay with a characteristic half-life. The energy of the neutrons which are bombarding the nucleus will dictate the type of interaction that occurs and the nature of the activated product. Interferences may occur as the result of the same radionuclide being produced by activation of different target nuclei [4].

In this paper we establish the study sequence required to determine the feasibility of this method for the analysis of elements in mineral samples in the same state of humidity and with identical particle size. In this work, the gamma radiation reading is produced after the irradiation of the sample with neutrons (delayed). The equipment used consists of an Americium Beryllium source and a gamma rays detector together with a multichannel analyzer [5].

To design the experiment and interpret the results a rigorous knowledge of the reactions that occur between neutrons and each of the elements in a mineral sample is essential. This information can be obtained from the National Nuclear Data Center del Brookhaven National Laboratory.

2. Study of theoretical feasibility
The feasibility of using neutron activation to determine an element in a sample depends on several factors. These factors are shown as follow:

1. If a neutron source is available, the energy spectrum of this source is to be analyzed.
2. The proportion of a mineral element in the ore sample is analyzed. All the isotopes in the element need to be considered.
3. Set reactions of the element with neutrons from the source are recorded for later consideration. These reactions occur in a certain range of neutron energies.
4. Reactions previously obtained are analyzed and the reaction is selected if the product of each of the reactions is radioactive.
5. The cross section from each selected reaction is recorded, as well as the gamma radiation emitted by the product of the reaction and the decay time.
6. The process is repeated for all other elements of the sample, returning to step 2.
7. In selected reactions:
   - Those reactions with a low cross section are eliminated.
8. The interferences of those remaining are evaluated, i.e.,
   - if several reactions take place at the same element of interest or,
   - if several reaction products emit gamma rays of the same energy or with the same period of decay.

It is now possible to deduce whether an element of the mineral sample can be analyzed by neutron activation with this neutron source.

The following is a practical case for the feasibility study of neutron activation determination of silica content in a coal sample.

2.1. Study of theoretical feasibility. Practical example

As a practical example we studied the feasibility of the neutron activation technique for the determination of SiO$_2$ in a coal sample with an Americium Beryllium source. The proportion of Si atoms in silica is known and therefore, the number of nuclei of Si in the sample. Also known are the different natural isotopes of Si which are $^{28}$Si, $^{29}$Si and $^{30}$Si as well as their proportion 92.21%, 4.7% and 3.09%. There are other unstable isotopes, but these are not found in nature.

Neutrons interact with nuclei of Si leading to different reaction products. Reactions can be obtained from database EXFOR/CSISRS [6] and they are shown in table 1. This database is accessible through Internet and belongs to the National Nuclear Data Center at Brookhaven National Laboratory.

Table 1. Reactions of Si with neutrons.

| $^{28}$Si  | $^{29}$Si  | $^{30}$Si  |
|------------|------------|------------|
| 14-Si-28(n,2n)14-Si-27 | 14-Si-29(n,2p)12-Mg-28 | 14-Si-30(n,α)12-Mg-27 |
| 14-Si-28(n,A-Be-7)10-Ne-22 | 14-Si-29(n,α)12-Mg-26 | 14-Si-30(n,el)14-Si-30 |
| 14-Si-28(n,α)12-Mg-25 | 14-Si-29(n,el) | 14-Si-30(n,g)14-Si-31 |
| 14-Si-28(n,el) | 14-Si-29(n,g)14-Si-30 | 14-Si-30(n,inl)14-Si-30 |
| 14-Si-28(n,g)14-Si-29 | 14-Si-29(n,inl)14-Si-29 | 14-Si-30(n,n+p)13-Al-29 |
| 14-Si-28(n,inl)14-Si-28 | 14-Si-29(n,n+p)13-Al-28 | 14-Si-30(n,p)13-Al-30 |
| 14-Si-28(n,n+p)13-Al-27 | 14-Si-29(n,p)13-Al-29 | 14-Si-30(n,tot) |
| 14-Si-28(n,p)13-Al-28 | 14-Si-29(n,x)13-Al-28 | 14-Si-30(n,x)13-Al-29 |
| 14-Si-28(n,p+α)11-Na-24 | 14-Si-29(n,x)13-Al-28 | 14-Si-30(n,x)13-Al-29 |
| 14-Si-28(n,tot) | 14-Si-29(n,x)0-G-0 | 14-Si-30(n,x)0-G-0 |

From this database, the probability of each reaction with the neutron source mentioned above, also known as the cross section, is obtained, and it depends on nucleus type and on the neutron energy. The cross section is obtained for each of the reactions illustrated in table 1.

Subsequently, the study focuses on those reactions with a high cross section with neutrons in the energy range of 3-10MeV characteristic of an Americium Beryllium neutron source. Figure 1 shows
the cross section in barns of the reaction $^{14}\text{Si}{}^{28}(n,\alpha)^{12}\text{Mg}{}^{25}$ with respect to the incident neutron energy.

![Cross section graph](image)

**Figure 1.** Cross section of the reaction $^{14}\text{Si}{}^{28}(n,\alpha)^{12}\text{Mg}{}^{25}$.

In all the reactions illustrated in table 1, a reaction product is obtained. It is necessary to determine which are unstable isotopes, as well as their characteristics, since these isotopes can be detected by radiation detectors. To do this, database NuDat has been used [7]. For example, the reaction $^{14}\text{Si}{}^{28}(n,\alpha)^{12}\text{Mg}{}^{25}$ is discarded because the magnesium is stable and it cannot be detected by radioactive methods. In contrast, the reaction $^{14}\text{Si}{}^{28}(n,p)^{13}\text{Al}{}^{28}$ gives the nuclide $^{13}\text{Al}{}^{28}$ which is radioactive.

In the same database the decay characteristics of each unstable isotope have been obtained.

**Table 2.** Beta energy emission from the decay of $^{13}\text{Al}{}^{28}$.

| Parent Nucleus | Parent E(level) | Parent $T_{1/2}$ | Decay Mode | Daughter Nucleus |
|----------------|----------------|------------------|------------|-----------------|
| $^{28}\text{Al}$ | 0.0            | 2.2414 min       | $\beta^-$  | $^{28}\text{Si}$ |

The product of the above reaction, Al-28 has decay characteristics shown in tables 2 and 3.

**Table 3.** Beta and Gamma energy emission from the decay of $^{13}\text{Al}{}^{28}$.

| Energy (keV) | Intensity (%) |
|--------------|---------------|
| $\beta$: 1247.2 | 99.990        |
| $\gamma$: 1778.85 | 100.00        |

Noting these characteristics it is possible to detect $^{28}\text{Al}$ from measurement and registration of a gamma radiation of 1779 keV, when there are no interferences, i.e, those from any other radioactive
product emitting gamma rays in its decay in this amount of energy. Therefore, it is necessary to study all elements of the sample with neutrons and analyze all the reaction products, decay modes and gamma emission originating from the decay of all products. In this case, the evaluation and testing that there are no interferences have been done.

However, it could be that other reactions lead to gamma emissions of similar energy but neutron activation is still viable, as the probability of occurrence of these reactions is very small compared with the probability that the reaction under study is the origin.

The implementation process of the neutron activation consists of the irradiation of the coal sample with an Americium Beryllium source for a given time and the subsequent reading of gamma radiation around 1779 keV which corresponds to the decay of Al-28 for a period of time directly related to the period of decay of Al-28. There are mathematical procedures to optimize the activation time as well as reading to get a maximum signal.

3. Conclusions
The procedure allows us to determine the feasibility of using the neutron activation technique in elemental analysis of mineral samples. Required data in databases accessible from the Internet have been found. This procedure is applied to the analysis of SiO₂ in a coal sample and has been proven. The procedure is as follows:
- The nuclear reactions between neutrons and isotopes of Si are analyzed.
- Those that give rise to a radioactive product are selected.
- One of them has been identified as, 14-Si-28 (n,p)13-Al-28 , whose product is radioactive and emits gamma rays of energy 1779 keV with a decay time of 2.2 min.
- Measuring this radiation we get the concentration of Al-28, and know the concentration of Si-28 can be determined.
- In this case it has been checked that there are no interferences from other elements in the measurement and recording of gamma radiation. It has therefore been demonstrated that it is possible to determine the silica concentration in the sample from neutron activation analysis

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