

# Application of Neutron-capture to Elemental Analysis

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**Abstract** To many in our community the study of nuclear Physics is a mental exercise that strengthens the mind, and helps to accumulate the appropriate number of points for a BSc degree. In reality many of the fundamental concepts of Physics, and nuclear physics in particular, have led to significant improvements in the community. (ref. MRI, CAT, PET, radiation therapy, nuclear power). This paper addresses the use of neutron capture in the identification of elements in small amounts. Applications have significant import in environmental areas (ref. heavy metal detection, Ni-Cd battery recycling) and community health (ref. Drug detection). Here we address the problems of nitrogen detection in medical applications (protein measurement) and explosives detection (parcel bombs and landmines)

## 1 Introduction

One of the dangers of modern society is an increasing possibility of high-profile individuals and establishments being sabotaged by terrorists or other enemies, using explosives packaged in parcels or small articles of mail. Common scanning methods used in security situations are not effective in specifically detecting explosives. Metal detectors for example respond to metals only, which may or may not be an indication of an explosive device. The device described here is designed to detect the presence of the explosive itself. It is sensitive, specific and completely objective.

## 2 Theory

In this section we will discuss:

- The physics of radiative neutron capture
- The detection of the  $\gamma$ -rays
- Practical problems in application
- Design of the units
- Other applications

### 2.1 Neutron reactions

The interaction of neutrons with nuclei leads to a compound nucleus. As with our general discussion of CN we noted that

$$\sigma_t = \sigma_{sc} + \sigma_r$$

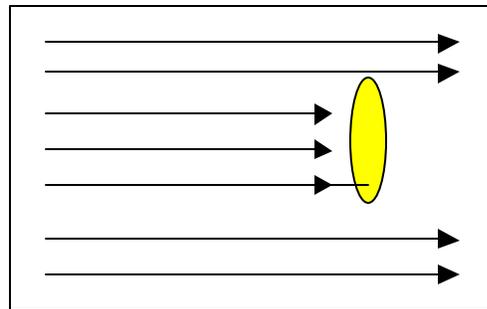


Figure 1

If we were to irradiate a nucleus with a beam of neutrons and assumed that the nucleus was “totally absorbing”, we might expect the reaction cross section  $\sigma_r$  to be given by

$$\sigma_r = \pi R^2$$

In reality, because the neutron has an interaction range the actual theory gives:

$$\sigma_r = \pi(R + \lambda)^2$$

The reality is that the total cross section is also equal to twice this value, and this results from the fact that there is of course diffraction around the “black sphere”. So that on this simple model:

$$\sigma_t = \sigma_{sc} + \sigma_r = 2\pi(R + \lambda)^2$$

This model assumes perfect absorption. In fact the probability of getting into the nucleus depends on the reflection at the boundary of the nuclear potential. In optics it is the same problem as reflection of light at the interface between air and glass.

The solution is done in section 2.3 of Krane and the resulting reaction cross section is.

$$s_r = p(R + \lambda)^2 \frac{4kK}{(k + K)^2}$$

$$K = \sqrt{2m(E - V) / \hbar^2} \text{ and } k = \sqrt{2mE / \hbar^2}$$

As the neutron energy gets lower,  $E \ll V_0$ ,

$$\lambda = k^{-1} \gg R \text{ and } k \ll K$$

so that 
$$s_r = \frac{4p}{kK}$$

$$k = 2\pi mv / \hbar \text{ so that}$$

$$\sigma_r \propto 1/v$$

This is known as the 1/v rule for neutron cross sections

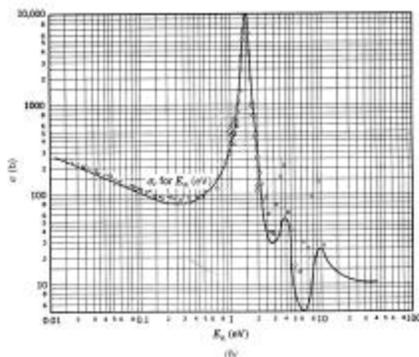


Figure 12.10 Resonances in neutron total cross sections. (a) A single isolated resonance superimposed on a 1/v background in Cd. (b) Several close-lying resonances in In. (c) Many sharp peaks in the resonance region in <sup>238</sup>U. (d) In <sup>32</sup>S.

The object of thermal neutron activation is to observe either an induced radioactivity (such as capture on indium as in the part 1 lab.), or  $\gamma$ -rays following the capture of a neutron. The  $\gamma$ -rays following the capture of the neutron and the formation of the compound nucleus,

are characteristic of that nucleus, and their identification can lead to identification of the presence of a particular element in an unknown sample. Hence our interest in the technique for identifying nitrogen in protein or in explosives.

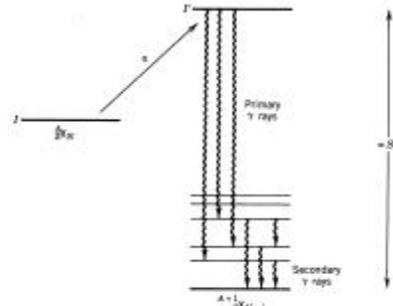


Figure 12.13 Low-energy neutron capture leads to a state  $I$ , which emits primary  $\gamma$  rays followed by secondary  $\gamma$  rays.

Since we want the maximum sensitivity, we want to have the largest possible neutron capture cross section. Hence since  $\sigma_r$  varies as  $1/v$ , we want to capture very low energy neutrons.

The reality is that all relatively convenient sources of neutrons give neutrons of high energy.

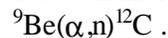
## 2.2 Some sources of neutrons

### 2.2.1 nuclear reactions

reaction	$E_n$	Reaction Q	characteristics
$d(d,3He)n$	Ed-Q	3.3 MeV	needs accelerator for d
$d(T,4He)n$	Ed-Q	17.6 MeV	needs accelerator for d
$^9Be(\alpha,n)^{12}C$	Ed-Q	5.7 MeV	needs accelerator for d

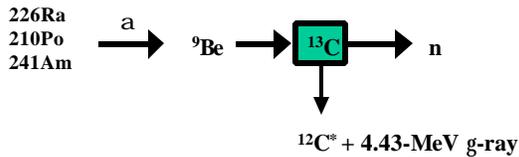
### 2.2.2 Radioactive sources

Most self-contained neutron sources are based on the reaction:



Note that a compound nucleus of  $^{13}\text{C}$  is formed and one of the decay channels is neutron emission. The sources can be made self-contained since the  $Q$  of the reaction is only 5.7 MeV, and several heavy radioactive nuclei emit  $\alpha$ -particles with sufficient energy to initiate the reaction. For example  $^{226}\text{Ra}$ ,  $^{210}\text{Po}$ ,  $^{241}\text{Am}$ .

### Encapsulated Neutron Source



The radioactive nuclide Thus we have sources where Be and the radioactive nuclide are intimately mixed together and sealed in a vial. (why?). These sources (you used a source of Am-Be in part 3) have two characteristics.

- the neutron spectrum is a mess

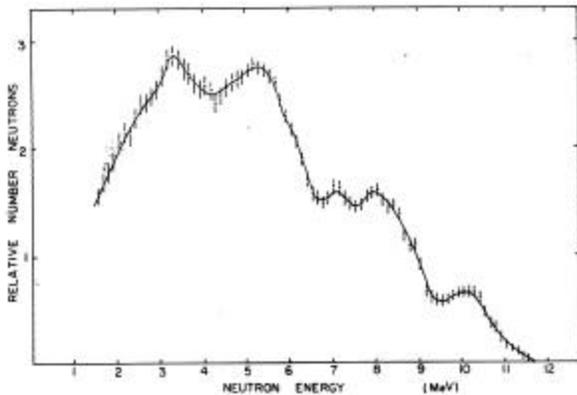


Fig. 1. Spectrum of neutrons from Am-Be source.

Ref. M. N. Thompson and J. M. Taylor. Nuclear Instruments and Methods **65**, 305 (1965)

- they all give a significant  $\gamma$ -ray flux, since the  $^{12}\text{C}$  that results is left in an excited state, predominantly the 1st excited state at 4.43 MeV. Hence in part 3 you used the Am-Be source as a source of high-energy  $\gamma$ -rays.

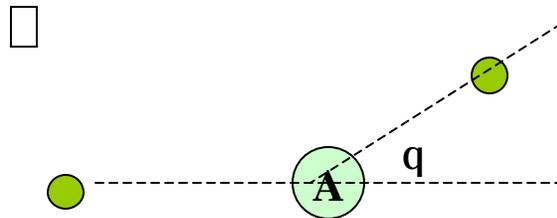
### 2.2.3 Spontaneous -fission sources

Certain heavy nuclei are inherently unstable against fission. One such is  $^{252}\text{Cf}$ . For this source there are no high-energy  $\gamma$ -rays, but again the neutron-energy spectrum is continuous.

### 3 Neutron Moderation

Whichever source is chosen to use, the energy of the neutrons is high, and hence the neutron-capture cross section is small. It is usual to reduce the neutron energy by a process called neutron moderation.

Remember that neutrons, unlike protons, do not lose energy by ionization, hence their range in matter is very long. The actual distance travelled before losing their energy or being captured is of order cm. As neutrons travel through matter they interact with nuclei. Some of these reactions lead to CN formation, and subsequent emission of reaction products. However one of the dominant reaction mechanisms is elastic scattering. In this process the neutron loses kinetic energy, and eventually is slowed down until it is in thermal equilibrium with the thermal KE of the particles in the medium.



The energy  $E_{sc}$  of a neutron of a neutron with initial energy  $E$ , after scattering off a target nucleus of mass  $A$  is given by:

$$\frac{E'}{E} = \frac{A^2 + 1 + 2A \cos \theta}{(A + 1)^2}$$

The maximum energy loss occurs for a head-on collision ( $\theta=180$ )

$$E'_{\min} = E \left( \frac{A-1}{A+1} \right)^2$$

Notice that for collision with a free proton (A=1), the neutron loses all its energy, so if an efficient moderator is needed hydrogen is a good choice. Free protons are found in water, and all hydrocarbons.

The average energy lost in a collision is quantified by the average logarithmic energy decrement which is simply related to E/E'

$\xi = [\log E/E']_{\text{av}}$  and depends only on A

$$\mathbf{x} = 1 + \frac{(A-1)^2}{2A} \log \frac{A-1}{A+1}$$

It is of course directly related to the average number of collisions a neutron makes before reaching thermal equilibrium

The moderating properties of certain materials are listed in table 1

**Table 12.1** Moderating Properties of Various Nuclei

Nucleus	$\xi$	$n$ (for thermalization)
<sup>1</sup> H	1.00	18
<sup>2</sup> H	0.725	25
<sup>4</sup> He	0.425	43
<sup>12</sup> C	0.158	110
<sup>238</sup> U	0.0084	2200

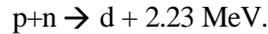
Moderator	Density $\rho$ (g.cm <sup>-3</sup> )	slowing down power $S$ cm <sup>-1</sup>	Moderating ratio $M$
Water	1.000	1.38	62.1
Heavy water	1.105	0.179	4040
Helium	$1.79 \times 10^{-4} @ 0^\circ\text{C}$	$8.68 \times 10^{-4}$	<6.44
Beryllium	1.848	0.156	137
Boron (amorphous)	2.37	0.060	0.000109
Carbon	2.000	0.075	230
Paraffin (CH <sub>2</sub> )	0.91	1.63	62.4
Lead	11.35	0.0036	0.64

**Table 2.5:** Slowing down power and moderating ratios for various materials. Apart from lead and boron, all of these materials are used as moderators.

Hydrogen is the clear selection for a moderating material, provided of course that we can get a reasonable density of nuclei. Taking the density of scattering centres into

account gives the following data. The measure of the effectiveness in slowing down the neutrons is the “slowing-down power”

As always life is not simple. Although hydrogen is the best moderator, it has a tremendous appetite for neutrons. We know this since we have studied the deuteron.



So although water quickly thermalises the neutrons, more of them are absorbed, so the flux of thermal neutrons is less. Heavy water, which has the H atoms replaced by 2H (deuteron), has had its appetite slaked, and the capture cross section for thermal neutrons is very small. The overall efficiency measure is indicated by the Moderating ratio, which is the ratio of the slowing-down power (S) to the effective capture cross section. The table shows that heavy water becomes the most suitable choice as a moderator.

The next table expresses these properties in terms of the path lengths of an average neutron. The moderation length T is the distance travelled by a neutron before reaching thermal energy. The diffusion length L is the average distance travelled before capture, and the migration length M is the vector distance travelled before capture.

Moderator	Diffusion length $L$ (cm)	Moderation length $T$ (cm)	Migration length $M$ (cm)
Water	2.88	5.74	6.43
Heavy water	100	10.9	101
Beryllium	23.6	9.90	25.8
Graphite	50.2	18.7	53.6

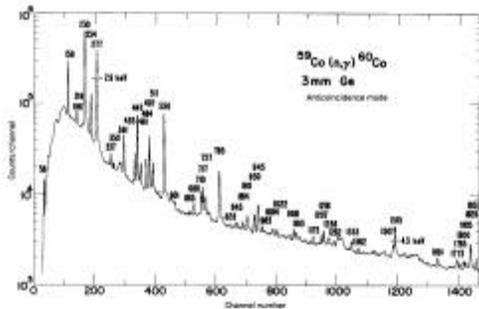
**Table 2.6:** Moderation lengths and migration lengths, for neutrons of a few MeV, for a few common moderating materials [Gl603a].

## 4 g-ray Detection

$\gamma$ -ray detection relies on atomic ionization processes where electrons are produced, and it is the energy of these electrons that is

measured as an indication of the detection of the  $\gamma$ -ray. Those who have done the Nuclear Lab. Will know that the Photo-electric effect, Compton scattering, and at high energies  $e^-e^+$  production are the processes.

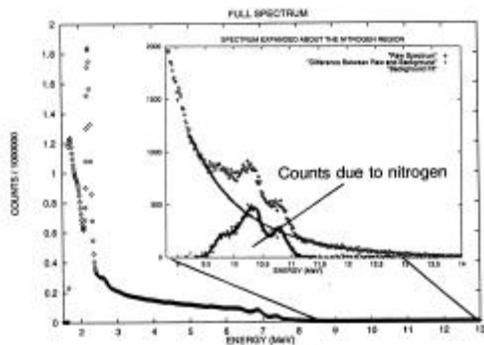
The energy of the capture  $\gamma$ -ray determines the size of the detector, and the required resolution determines whether efficient and cheap NaI detectors, (such as used in the Part 3 lab) or high-resolution, inefficient and expensive solid-state detectors are used.



Further details of this will be published in a separate paper.

**4.1 Spectrum from neutron capture on  $^{14}\text{N}$**   
 Neutron capture by the nucleus  $^{14}\text{N}$  leads to emission of a  $\gamma$ -ray of energy 10.83 MeV. To detect this efficiently a large NaI detector is required. However because of the high background, which is due to neutron capture in the surroundings, and the detector itself, we are limited to a 3 inch x 3 inch detector.

A typical spectrum is shown in the next figure



The spectrum of  $\gamma$ -rays from a sample of nitrogen-containing material. The 10.8-MeV  $\gamma$ -ray indicating the presence of nitrogen is indicated. Note the vertical scales relevant to the different regions of the spectrum

Several points should be noted with regard to this spectrum:

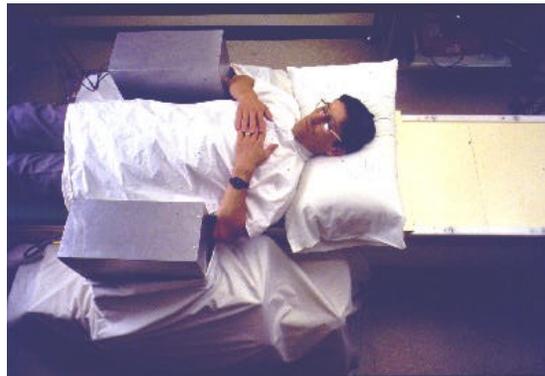
- Evidence of the relevant  $\gamma$ -ray can be clearly seen at the maximum energy region of the spectrum.
- The number of  $\gamma$ -rays is extremely small, only being evident when the spectrum is magnified by many orders of magnitude. As such, although providing evidence of the presence of nitrogen, would in this form be unsuitable for a fast, objective detection device.
- The vast majority of the spectrum is due to  $\gamma$ -rays from other elements, particularly from neutron capture on hydrogen (2.23 MeV). This tends to obscure the relevant 10.8-MeV  $\gamma$ -ray.
- The response of the detector to the 10.8-MeV  $\gamma$ -ray lies on a smooth background that contains the same order-of-magnitude of counts as the nitrogen  $\gamma$ -ray. This smooth underlying continuum results from the random overlap of smaller pulses, (pile-up), and would lead to a lack of reproducibility if this simple system were to be used.

## 5 Specific Applications

### 5.1 Total body protein system

The first application where we used this technique was to determine the protein content of the human body. Protein is the only compound in the body containing nitrogen, and so was very suitable to TNA.

In this case a  $^{252}\text{Cf}$  fission source was used for the unit, and the water in the body was



the moderator.

## 5.2 SNUPA Parcel-bomb detector

### Design of Unit

So far we have not discussed the distribution of thermal neutrons if we have a source in a moderator.

Ignoring capture, we know that in the steady-state condition, the number of neutrons emitted/sec from the source equals the number of neutrons diffusing past a sphere of radius  $R$ /sec. So that the thermal neutron flux, or the number of neutrons passing unit area/sec= $Q/(4\pi R^2)$ . (How would you measure this?)

This means that if you wanted to get the maximum thermal activation of a sample, it should be placed next to the source. In the part 1 expt where indium is activated, this is so. In the present application this is impossible, and the difficulties associated with our projects will be discussed in this section.

### Development of the Prototype

We subsequently developed from the proof-of-principle unit, a prototype, which is designed not only to be suitable for routine office use, but which has significantly improved sensitivity and reliability as a result of addressing the problems arising from the observations outlined above.



Figure 2 The SNUPA Prototype

The features of the SNUPA prototype include:

- The type, amount, and geometry of the moderating material have been optimized to improve the sensitivity.
- Novel and innovative electronics has been introduced to minimize the underlying pile-up. Thus the underlying background under 10.8-MeV  $\gamma$ -ray has been virtually eliminated.
- This pile-up removal has eliminated the need to record a spectrum, so that a simple sum of events in the 10.8-MeV region will suffice.
- The insensitivity to pile-up means that a stronger neutron source can be used without compromising the unit's reliability.
- The use of several  $\gamma$ -ray detectors is now possible, with a consequent increase in sensitivity.

## 5.3 Humanitarian applications

### Anti-personnel landmine detector



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<sup>1</sup> The authors wish to acknowledge the interest and patience of the students attending (and sleeping through) the class. They also hope that the problems set for each lecture are being attempted, and that the results in the final examination will truly reflect the effort expended.