PHY3004W Laboratory
Neutron activation of ^{27}Al

Dr. Tanya Hutton

tanya.hutton@uct.ac.za

RW James 2.36

Introduction

The development of nuclear technology is one of the most significant achievements of the twentieth century and is used in nearly every aspect of our lives from medicine, to manufacturing and construction, and to producing electricity for over 16% of worldwide needs.

New isotopes are still being discovered, with a further 36 new discoveries from 2019-2022, bringing the total number of observed isotopes to 3338 [1] with thousands more predicted through nuclear models. This considerable progress is owed to the discovery of new reaction types along with the development of powerful accelerators and experimental techniques for separation and identification of reaction products.

In 1934 Irene Curie and Pierre Joliot first demonstrated the production of artificial radioactivity in the laboratory by irradiating a natural aluminium sample with alpha particles emitted from a polonium source. A nuclear reaction occurred between the alpha particles and the stable ^{27}Al nuclei to produce radioactive ^{30}P, a positron emitting isotope. In 1935 they were awarded the Nobel Prize in Chemistry for this work [2].

Locally, radionuclides are regularly produced for medical applications at iThemba LABS using proton beams, and at Pelindaba using the neutrons produced by the SAFARI-1 research reactor. Within the Metrological and Applied Sciences University Research Unit (MeASURe) at the University of Cape Town, artificially produced radioactivity plays a large part in the nuclear research programs, from neutron activation analysis at the n-lab, tracer production for positron emission particle tracking (PEPT), and dose verification in proton therapy.

In this laboratory you will explore the different nuclear reactions that can occur when natural aluminium (^{27}Al) is irradiated with neutrons.

Neutron reactions

Neutrons are uncharged, which means they can interact directly with the atomic nucleus with a finite probability. This probability is related to the reaction "cross section", which is the effective area of the nucleus presented to the incoming particle. Many different types of reaction may take place with differing cross sections depending on the energy of the incoming neutron.

Neutrons can be broadly classified by their energy as:

- thermal (E = 0.025 eV);
- epithermal (0.025 eV $<$ E $\leq$ 0.1 MeV); and
- fast (E $>$ 0.1 MeV).

One of the common interactions at thermal and epithermal energies is radiative capture, where the incident neutron is captured by the target nucleus followed by de-excitation via the (almost) instantaneous emission of at least one gamma ray. The radiative capture of a neutron incident on ^{27}Al can be described by:

$$^{27}\mathrm{Al} + \mathrm{n} \rightarrow {}^{28}\mathrm{Al}^{*} \rightarrow {}^{28}\mathrm{Al} + \gamma.$$

Alternatively, this can be written in a more concise notation as ^{27}Al(n,γ)^{28}Al. The resulting ^{28}Al nucleus is unstable and undergoes β^- decay to ^{28}Si.

The radiative capture of a neutron is just one example of the many possible reactions that neutrons might have with ^{27}Al. Some other reactions require the incident neutron to have a minimum energy such as those that emit secondary particles (neutrons, proton, deuterons and alpha particles). Figure 1 shows a selection of possible reaction pathways for a range of different incident particles.

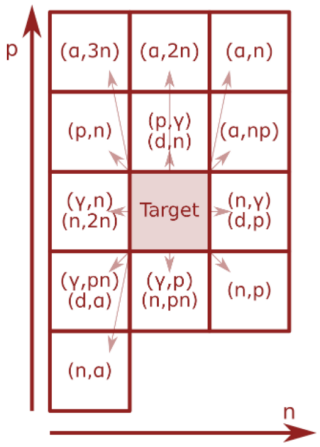

Figure 1: Common nuclear reaction pathways for neutrons (n), gamma rays (γ), protons (p), deuterons (d), and alpha particles (α) incident on a target nucleus as a function of neutron and proton number.

Radioactive decay law

The decay rate of a large population of radioactive nuclei, whether from natural or artificial origins, decreases with time according to an exponential law. However, the disintegration of any single nucleus is spontaneous and impossible to predict as radioactive decay is statistical in nature.

If N radioactive nuclei are present in a sample at time t then the rate of change of the number of nuclei (dN/dt) is proportional to N as:

$$\frac{dN}{dt} = -\lambda N,$$

where λ is the decay constant and is characteristic property of the parent nucleus and decay type. Integrating this expression leads to the exponential decay law:

$$N(t) = N_0 \exp -\lambda t,$$

where N_0 is the number of nuclei present at time $t = 0$ [2]. The half-life $t_{1/2}$ is then defined as the time required for half of the parent nuclei to decay ($N(t) = N_0/2$), and is related to the decay constant as:

$$t_{1/2} = \frac{\ln 2}{\lambda}.$$

The half-life, decay type and decay products are characteristic for each radioactive isotope. In the case of the β^- decay of ^{28}Al, it has a half-life of (2.245±0.002) minutes, followed by the highly probable emission of an associated gamma ray at (1778.987±0.015) keV [3].

Experimental Procedure

The aim of this laboratory is to investigate the different gamma ray emitting isotopes produced during the neutron activation of ^{27}Al through the measurement and analysis of time-dependent gamma ray spectra.

In PHYLAB3 you will have have access to a 2.2 GBq americium-beryllium (AmBe) radioisotopic neutron source. Americium-241 is unstable and decays to ^{237}Np through the emission of an alpha particle, which can then be captured by ^{9}Be to produce ^{12}C, a neutron, and a gamma-ray [4]. The energy of neutrons emitted by the source range from thermal up to ∼11 MeV. The AmBe source is the most active source in the laboratory and will be situated in a water bath which acts as a neutron shield and moderator[1]. Note that high-energy gamma rays are produced by the source and from neutron interactions with the surrounding materials so minimise your time in close proximity to the water bath. **Under no circumstances should you remove the AmBe source from the water bath.**

Natural aluminium (^{27}Al) cylinders will be placed in the water bath with the neutron source to induce radioactivity. If there are other students using the laboratory make sure to co-ordinate so you minimise disruption to each others' experiments. Your aluminium cylinder will need to be activated for a minimum of 60 minutes.

In this experiment you will be using a ⌀5 cm x 5 cm NaI(Tl) scintillation detector as with the previous gamma spectroscopy laboratory. Set up your detector system to cover a sensible energy range by changing the amplifier settings, and then calibrate the pulse height scale using the gamma ray reference sources [5].

Next, set up the acquisition software USX [6] to measure multiple spectra over a period of time. Go to *Spectrum→Setup Multiple Runs* and test this feature before you try to measure with the activated aluminium cylinder. Once you are satisfied that this is behaving, prepare a multiple run to acquire spectra in short time intervals of your choosing for a minimum total acquisition time of 60 minutes.

Extract the activated aluminium cylinder from the water bath, and wipe dry before moving it to the detector station. You will need to work quickly, but safely, to ensure that you acquire sufficient data before the activity is reduced to sub-background levels. Very carefully place the NaI(Tl) inside the neutron activated cylinder. Avoid touching the photo-multiplier tube (PMT) and connectors due to high-voltage and risk of injury due to shock. When the detector is in place, start the multiple runs.

Analysis of gamma ray spectra

Once you have acquired your data you will have access to both energy and time information to help identify the different radioisotopes that may be present.

After calibration sum your spectra measured over multiple short time intervals to produce a single long duration spectrum that can be used to identify the energy of the different features. Consider what might be associated with the natural background, and what can be attributed to the activated aluminium.

Next investigate the time dependence of your measured data by producing a decay curve. From each gamma ray spectrum determine the total count rate and associated uncertainty, and plot as a function of time. Consider the functional form of the produced curve and how this might relate to the exponential decay law. What if there are two or more gamma ray emitting isotopes present, each with different half-lives? It may be enlightening to plot your decay curve on a logarithmic y-scale and investigate the decay curves associated with different energy ranges.

[1] Refer to the supplementary document *Neutron radiation from ^{241}Am-Be* for more details.

You will need to use fitting techniques to try and determine the half-life of isotopes produced during neutron activation and use this information to aid in the identification of the different contributions. You should consider very carefully your choice of curve-fitting methods [7], and be able to explain why it is the appropriate method for your data. Directly fitting a non-linear function to the decay curve can lead to unexpected or non-physical results, with a strong sensitivity to initial guesses of parameters. However, if you are able to linearise your data set then simpler and more robust fitting techniques are available [8], such as the method of weighted linear least squares [9]. Consider how you can demonstrate the quality of your fit relative to your measured data [10].

Compile a list of observed gamma ray emissions and estimates of the half-life for the different contributions, with their uncertainties, and use these to identify which radioisotopes may be present in your measured spectra through a search of nuclear databases such as the table of gamma rays from KAERI Nuclear Data Centre [11]. Use your knowledge of nuclear reactions to help exclude unlikely candidates.

Assessment

There are two components to the assessment of this laboratory. You will need to upload a unique data set to Amathuba assignments at the end of week two (17:00 Friday 16 May 2025), which will contribute 5% to the overall assessment. The remaining 95% is associated with a concise 4-page report on the neutron activation of ^{27}Al to be submitted via Amathuba assignments by 17:00 Friday 23 May 2025. Further details on the assessment will be provided in a supplementary document.

References

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[4] Hutton, T., *Neutron radiation from ^{241}Am-Be*, University of Cape Town (2024).

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[6] Spectrum Techniques, *UCS-30 universal computer spectrometer*, `https://www.spectrumtechniques.com/wp-content/uploads/UCS30-Manual.pdf` [accessed 20 July 2023].

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[9] Kirkup, L., *Experimental methods for science and engineering students*, Cambridge university press, second edition, (2019) pp 111-132.

[10] Bevington, P., *Data reduction and error analysis for the physical sciences*, McGraw-Hill, third edition (2003), pp 194-216.

[11] KAERI Nuclear Data Centre, `https://atom.kaeri.re.kr/old/gamrays.html` [accessed 01 March 2024].