Neutron Activation Analysis Activity, NSSC Summer School 2019, UC Davis

1 Purpose

Neutron activation allows a scientist to calculate some of the unknown trace contents of a sample by creating short-lived radioisotopes through neutron capture or other neutron reactions on the nuclei of trace elements. Students will learn how to analyze irradiated samples, identify unknown elements, and calculate the concentration of a contaminant in a real liquid sample using a calibration foil.

Activity 1

For this activity, you will be identifying a contaminant in a real sample of organic liquid. You will also be identifying the element of metal in a foil that will be used as a calibration source. One pair of students should concentrate first on the unknown liquid contaminant, and one should concentrate on the metal. Once your pair has identified their sample, switch to the other sample, and feel free to take hints and get help from the other pair.

Activity 2 - advanced

Use the calibration foil to identify the flux of thermal neutrons at the sample's position in the reactor (your scintillator sample and foil should have been irradiated at the same position in the reactor and measured with the same HPGe detector.) Use this calculation of the thermal neutron flux to measure the concentration of the contaminant.

2 Setting Up

At this point, a calibration foil and contaminated liquid sample should both have been prepared and irradiated at the MNRC reactor facility in Sacramento. The data from gamma counting of each sample should have been transferred to the local computer cluster by your instructor.

Log into the NAT computers in room 392 with this username and password:
Username: nat
Password: LearnNuclearTechniques

Open up a terminal window and enter the directory for NAA Analysis using these instructions:
Click on the purple search icon and type "terminal" into the search browser
Click on the terminal application

Enter the working directory for this project:

```
cd /home/nat/NAA_Analysis
```

Practice opening the program "root", loading the analysis script, drawing the calibration spectra, and fitting a Gaussian function to a chosen peak.

```
root -l
.L NAA_Analysis.C
NAA_Analysis("<group letter>", "C")
```

Two windows should appear, both showing the same spectra but one showing a log scale and one showing a linear scale. Practice zooming in on certain lines (click and drag) and un-zooming to show the full spectra again (left click on axis and select "Unzoom"). Get help from your instructor if necessary. Zoom in on a peak until you can resolve the center to within 1 keV. Choose a tight region around the peak and fit it to a Gaussian+Error function+constant with the following commands:

```
FitPeak(<low>, <center>, <high>)
```

with <low> and <high> the chosen lower and upper values for your fitting threshold. If the fit fails visibly with the parameters you have input, try increasing or decreasing your fit window.

To exit the program, type

```
.q
```

Next, draw the spectra of the contaminated scintillator.

```
root -l
.L NAA_Analysis.C
NAA_Analysis(<group number>, "L")
```

Now you are ready to start the exercise. Within your group of four students, decide which two will work first on identifying the calibration foil and which will work on identifying the unknown scintillator contaminants.

3 Activity 1

Calibration foil
The calibration foil is made up of a nearly pure metal element, which may be comprised of more than one isotope of this element. There may also be contaminants in the metal. Find gamma lines in your spectrum that correspond to the decay of certain isotopes. Identify other gamma lines that should be present from the decay of that isotope and observe whether or not they are present in your spectra. Write down all radioactive isotopes that you have determined to be present in the sample and use them to identify the main element in the foil. Identify any contaminants you measure to be present. Use the worksheet "Calibration foil" at the end of this document as a guide.

Liquid Contaminant
The organic liquid "LAB", or Linear Alkyl-Benzene, is used as scintillator in many experiments. A real sample of LAB from the SNO+ experiment with a known contaminant has been irradiated. The scintillator is comprised of many carbon, hydrogen, and oxygen atoms. All of these elements can capture neutrons or react in other ways with high energy neutrons, but the product of the neutron capture or other surrounding isotopes on the nuclear isotope chart is always stable or nearly stable. You will most likely not see any signal from these elements, which means that any signal that you do see is a contaminant. Find gamma lines in your spectrum that correspond to certain isotopes, and identify the number and nature of any contaminants that you find. Use the worksheet "Liquid Contaminants" at the end of this document as a guide.

Tools
The website `http://nucleardata.nuclear.lu.se/toi/` provides "Radiation Search" and "Nuclide Search" functions. To identify a particular gamma line, click on "Radiation Search" and enter the energy of your gamma line of interest, within ± 1 keV. Refine your search by constraining the half-life of the isotope in question. Since the decays are occurring within a few hours of irradiation, the half-lives are most likely shorter than 5 days.
The **Ig(%)** column shows the intensity of the gamma line (how often a gamma of this energy is emitted in the decay process). With the short HPGe exposure times or our samples, we will probably only see gamma lines with significant intensities ($>1\%$). If a gamma line has an intensity of $\ll 1\%$ from a particular isotopic radioactive decay, this is probably not the isotope producing the gamma.
If a candidate parent isotope looks promising, click on that isotope name to redirect to its information page. A list of other gammas emitted from its decay should be listed. Are the high intensity gammas from this list present in the spectrum? Use this information to determine if a candidate isotope is likely in your calibration foil.
The **Nuclear Isotopes** books also provide this information and can be used as a tool.

Tips
Along with the gamma lines from your irradiated sample, there may be other lines present. There is air inside of the container, and there are nuclear isotopes in that air which may become irradiated and decay, emitting gammas. There may also be electron/positron pair production from high energy gamma lines. When a positron is created, it annihilates with the surrounding matter, and two gamma lines of 511 keV are produced.

4 Activity 2

4.1 Find the low-energy neutron flux at the irradiation position in the reactor

The radioactive isotopes that are created through thermal neutron capture are constantly decaying throughout the irradiation time, time between irradiation and counting, and during counting, with the relationship

$$N = N_0 e^{-\lambda t}, \tag{4.1}$$

where N is the number of isotopes remaining after time t, N_0 is the initial number of radioactive isotopes, and λ is the decay constant ($\lambda = ln(2)/t_{1/2}$, where $t_{1/2}$ is the halflife of the sample.)
The activity of the sample immediately after irradiation is given as the following:

$$A_i = n \cdot \phi \cdot \sigma(1 - e^{-\lambda t_i}), \tag{4.2}$$

where n is the initial number of target atoms in the sample, ϕ is the reactor flux, and σ is the thermal neutron capture cross section of the target isotope.
After folding in the decay times for the counting time and the time between irradiation and counting, the flux can be calculated as:

$$\phi = \frac{N_c}{n \cdot \sigma \cdot \epsilon \cdot I_\gamma}\Big(\frac{\lambda}{1 - e^{-\lambda t_c}}\Big)\Big(\frac{e^{-\lambda t_d}}{1 - e^{-\lambda t_i}}\Big), \tag{4.3}$$

where N_c is the number of counts detected from a particular gamma line, n is the initial number of target atoms, ϵ is the gamma detection efficiency of the detector, I_γ is the intensity of that gamma from decay of the isotope of interest, t_c is the counting time, t_d is the time between the irradiation and counting, and t_i is the total time of irradiation.
We will use the calibration foil to calculate the low energy neutron flux at the core of the reactor. Choose the largest gamma line produced by neutron capture. The reason that we use a gamma line from neutron capture is that this reaction is much more likely to occur at low neutron energies where other neutron reactions occur at high energies, as illustrated by the figure below for neutrons incident on ^{40}Ar (source: `http://nucleardata.nuclear.lu.se/toi/`) Use the worksheet provided below as a guide.

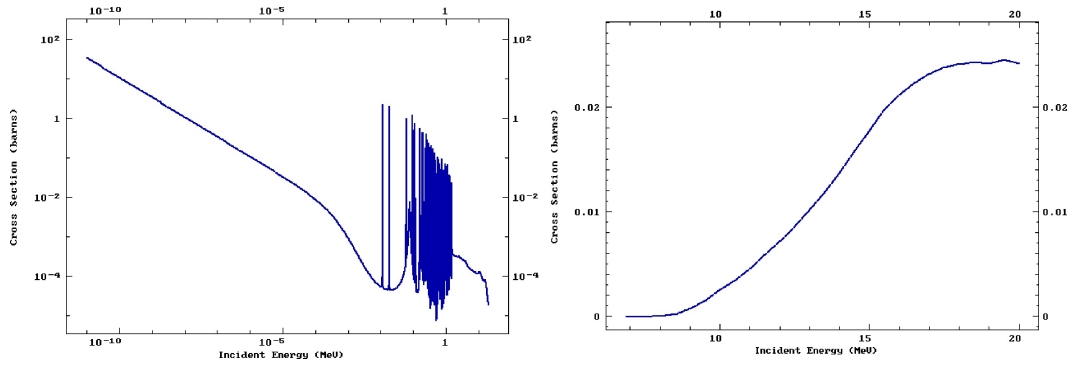

Figure 4.1: Cross section for neutron capture (left) and (n,p) reaction (right) for neutrons incident on ^{40}Ar as a function of neutron energy.

Worksheet:

Find N_c

Fit the gamma line that you will use for this measurement with the fitting function provided. The integral should be displayed.

Gamma line chosen:_____ Integral of gamma peak:_____

We need to take into account any "dead time" from the HPGe detector. Dead time occurs when the frequency of gammas being detected is too high for the data acquisition system of the detector to keep up in its recording, and some events are missed. The "livetime" and "total time" are lines 1&2 of the data file used to create the spectra. Find them by typing the following commands into the terminal:

```
less Spectra/Spectra_Group<group letter>_C.TKA
q
```

Livetime:_____ Total time:_____

The number of detected decays will be the integral*(total time / livetime). Write N_c in the provided table below.

Find n

Find the number of target atoms of the isotope of interest. Be mindful of units.

(foil mass)*(natural abundance of isotope)*(number atoms per mole)/(molar mass of foil)

Write n in the table below.

Find σ

Find the thermal neutron (0.025 eV) capture cross section on the isotope of interest. Go to this NIST website: `https://www.ncnr.nist.gov/resources/n-lengths/` and click on the element of interest. The thermal neutron cross section, in units of barns, is under the column labeled **Abs xs**. Convert this number to cm^2 with the relationship 1 barn =

1	γ Energy (kev)	Efficiency		**2**	γ Energy (kev)	Efficiency
	88.00	0.0884			88.00	0.159
	122.10	0.0798			122.10	0.140
	165.90	0.0619			165.90	0.106
	279.20	0.0386			279.20	0.0735
	391.70	0.0259			391.70	0.0526
	661.70	0.0142			661.70	0.0324
	898.00	0.00963			898.00	0.0221
	1173.20	0.00735			1173.20	0.0174
	1332.50	0.00638			1332.50	0.0155
	1836.10	0.00457			1836.10	0.0115
3	γ Energy (kev)	Efficiency		**4**	γ Energy (kev)	Efficiency
	88.00	0.154			88.00	0.105
	122.10	0.173			122.10	0.149
	165.90	0.154			165.90	0.157
	279.20	0.122			279.20	0.1345
	391.70	0.0878			391.70	0.104
	661.70	0.0583			661.70	0.0759
	898.00	0.0391			898.00	0.0511
	1173.20	0.0316			1173.20	0.0429
	1332.50	0.0285			1332.50	0.0392
	1836.10	0.0221			1836.10	0.0318

Table 4.1: Table of detection efficiencies for a range of photon energies for the HPGe detectors at MNRC reactor facility.

10^{-24} cm^2, and write this number in the table provided below.

Find ϵ
To find the efficiency of the HPGe detector to detect the gamma ray of interest, ask your instructor if your group used detector 1, 2, 3, or 4. Then consult the efficiency table and interpolate between gamma energies if needed. Write down the efficiency in the table below.

Find λ
Look up the half-life of the decaying isotope you have chosen to study. Convert from half-life to mean lifetime and write the value in the table below.

Find t_i
The irradiation time (seconds) is the total time that the sample was in the reactor core.

Find t_d

N_c	
n	
σ	
ϵ	
λ	
t_i	
t_d	
t_c	

Table 4.2: Enter variable values for thermal neutron flux calculation.

Calculate the number of seconds between the end time of irradiation and the start time of HPGe counting.

Find t_c
The total counting time (seconds) is the value you have written as the "Total time" of counting above.

Find Thermal Neutron Flux at Irradiation Location
Calculate.

The thermal neutron flux at the point of irradiation is _____.

4.2 Find the concentration of the contaminant in the sample

We first want to be sure that the contaminant is in fact in the liquid, and not a contaminant of the air or plastic vial. Since the calibration foil and liquid were irradiated in the same type of vial under the same conditions, any contaminant of the container itself will be present in both.
Write down the contaminants that you see in both the calibration and liquid samples:
_____
Write down the contaminants unique to the liquid: _____

The gamma line that you choose to analyze might come from a primary (directly from neutron capture) or secondary (created after decay) isotope. If it is secondary, compare the half-life of the secondary to primary isotopes. If the ratio of secondary to primary is > 10 and the start of the counting time is at least four half-lives from the irradiation time, we can consider the time lapse between primary and secondary decays negligible for our analysis and use equation 4.3 to be an equation for the number of target atoms:

ϕ	
N_c	
σ	
ϵ	
λ	
t_i	
t_d	
t_c	

Table 4.3: Enter variable values for liquid contaminant calculation.

Re-perform the calculations for the variables from section 4.1 and write them in the table above. If it is a secondary reaction, use the mean lifetime (λ) of the secondary isotope. Calculate n and convert to grams. Find the concentration of the contaminant as a function of g/mL of the liquid.
To find the live and dead time of the HPGe detector, use the following command:

```
less Spectra/Spectra_Group<group letter>_L.TKA
q
```

5 Worksheet: Calibration Foil

Worksheet:
Write down the energies of the ten largest gamma lines that you see.

Use the `http://nucleardata.nuclear.lu.se/toi/` website to identify candidate isotopes and accompanying gamma lines. Use the back of this worksheet as scratch paper if needed.
Write down the radioactive isotopes that you see:

The isotopes present in the original sample prior to irradiation are not the isotopes which are decaying and emitting gamma lines. The isotopes decaying are produced by one of the reactions listed below:
$X_A^Z(n,\gamma)X_{A+1}^Z$
$X_A^Z(n,2n)X_{A-1}^Z$
$X_A^Z(n,3n)X_{A-2}^Z$
$X_A^Z(n,p)X_A^{Z-1}$
$X_A^Z(n,d)X_{A-1}^{Z-1}$
$X_A^Z(n,t)X_{A-2}^{Z-1}$
$X_A^Z(n,\alpha)X_{A-3}^{Z-2}$

A particular fast-decaying isotope could have also decayed away in minutes to produce the isotope that is observed through gamma emission. Group together isotopes with similar Z and A values to determine which might have come from the same parent element to separate the foil element from contaminants.

Identify the element of the calibration foil:

Identify any contaminants:

6 Worksheet: Contaminated liquid

Worksheet:
Write down the energies of the two largest gamma lines that you see.

Use the `http://nucleardata.nuclear.lu.se/toi/` website to identify candidate isotopes and accompanying gamma lines. Use the back of this worksheet as scratch paper if needed.
Write down the radioactive isotopes that you see:

The isotopes present in the original sample prior to irradiation are not the isotopes which are decaying and emitting gamma lines. The isotopes decaying are produced by one of the reactions listed below:
$X_A^Z(n,\gamma)X_{A+1}^Z$
$X_A^Z(n,2n)X_{A-1}^Z$
$X_A^Z(n,3n)X_{A-2}^Z$
$X_A^Z(n,p)X_A^{Z-1}$
$X_A^Z(n,d)X_{A-1}^{Z-1}$
$X_A^Z(n,t)X_{A-2}^{Z-1}$
$X_A^Z(n,\alpha)X_{A-3}^{Z-2}$

A particular fast-decaying isotope could have also decayed away in minutes to produce the isotope that is observed through gamma emission. Group together isotopes with similar Z and A values to determine which might have come from the same parent element to separate the foil element from contaminants.

Identify any contaminants in the organic liquid: