Nuclear Lifetimes

Theory

The measurement of the lifetimes of excited nuclear states constitutes an important experimental technique in nuclear physics. The lifetime of a nuclear state is related to its width, \( \text{width} \), by the uncertainty principle:

\[
\Delta E \Delta t = \hbar \quad \text{(Eq. 1)}
\]

where \( \Delta E \) = uncertainty in energy associated with a state,
\( \Delta t \) = uncertainty in time associated with the state,
\( \hbar = 1.054 \times 10^{-34} \text{ joules-sec} \).

In general, for nuclear lifetimes, Eq. (1) becomes

\[
\tau = \frac{\hbar}{\Gamma} \quad \text{(Eq. 2)}
\]

Where \( \tau \) = mean life of a level of width \( \Gamma \).

This experiment will use the coincidence method of timing identification to measure the mean lifetime in the decay scheme of \(^{57}\text{Co}\).

The decay scheme for \(^{57}\text{Co}\) is shown in Figure 1a. The decay of this isotope is essentially all by electron capture, (EC), to the 136 keV level of \(^{57}\text{Fe}\). Figure 1b shows a high-resolution x-ray spectrum of \(^{57}\text{Co}\), in which the \( K_{\alpha 1} \) and \( K_{\beta 1} \) x-rays resulting from the electron capture are shown. The decay of the 136 keV level of \(^{57}\text{Fe}\) can occur by one of two principal modes: by a 136 keV gamma directly to the ground state or by branching through the 14 keV level to ground state.
The 136 keV gamma, $\gamma_3$, branch occurs 11% of the time. The 122 keV gamma, $\gamma_2$, is 87% abundant. The 14 keV level, $\gamma_1$, de-excites most of the time by internal conversion. The ratio of internal conversion to gamma decay, $\text{e/}\gamma$, for this level is ~9.0.

Figure 2 shows a high-resolution gamma spectrum of a $^{57}$Co source. The lifetime of the 14 keV state can be measured by determining the time distribution of coincidence events between $\gamma_2$ and $\gamma_1$. The accepted value for this lifetime is 98 ns.

Experimentally the best way to do this delayed coincidence experiment is with a time-to-amplitude converter (TAC). In this experiment, $\gamma_2$ will be used to start a time measurement, and $\gamma_1$ will be used to stop the measurement. The output of the TAC will then provide a time distribution of the lifetime of the first excited state of $^{57}$Fe, calibrated with known delays.
Experiments

I Measurement of gamma spectra

Use the 2×2 inch NaI detector to collect a gamma spectrum of the $^{60}$Co source. The figure shows the set-up using the detector, high voltage supply (1000 V for both detectors used here), preamplifier, main amplifier and MCA (Multi-Channel Analyzer - a PC card). Observe the preamplifier and main amplifier pulses with the oscilloscope. The spectra show two peaks, at 1175 and 1333 keV. Print the spectrum, and identify the peaks. Replace the $^{60}$Co source with the $^{57}$Co source and repeat the procedure.

![Figure 3: Electronic Block Diagram for Gamma-Ray Spectroscopy System with NaI(Tl) Detector](image)

Next, use the thin window NaI detector to collect the 14.4 keV gamma spectrum from the $^{57}$Co source. Compare the $^{57}$Co spectra with the spectra shown on Figures 4a and 4b.

Fig. 4a shows a typical spectrum of $^{57}$Co as it will appear at the output of the amplifier connected to the NaI (TI) 2x2 inch detector. Note that the 122 keV and 136 keV lines are not resolved in the spectrum as they were when taken with an HPGe detector as shown in figure 2.

![Figure 4:](image)

(a) Spectrum of $^{57}$Co taken with 2x2 inch NaI(Tl) Detector. (b) Spectrum of 14.4 keV Gamma from $^{57}$Co taken with Thin-window NaI(Tl) Detector.
II  Measurement of the time resolution of the system

Figure 5: Electronics for Lifetime Measurement with TAC.

Figure 5 shows the electronics that will be used for this experiment. In order to measure the time resolution, the detectors' high voltages are switched off so that only the split (and therefore coincident) pulses from the pulser are used. The timing SCA (Single Channel Analyzer) puts out both a +5 V slow pulse and a -0.8 V fast pulse each time the SCA records an event. For timing experiments with a TAC (Time-to-Amplitude Converter), the fast negative pulse is always used.

The TAC is essentially a fast electronic stopwatch. We provide it with a start pulse to start its timing sequence and a stop pulse to stop its sequence. The time difference between the start and stop pulses is $\Delta T$. The TAC gives us an output that is proportional to $\Delta T$. In other words, if $\Delta T = 1 \mu\text{sec}$, the output of the TAC might be a 1 V pulse. If $\Delta T = 2 \mu\text{sec}$, the TAC would give a 2 V pulse, etc. If we then consider what the TAC does, it not only says that two events are in coincidence, but it also tells us how these coincidences are distributed with respect to time. The full-scale range of the TAC can be set from 50 nanoseconds to several milliseconds from the front panel. As we will see, for many applications, it is the best way to do coincidence spectroscopy.
Procedures

1. Set up the electronics as shown in Figure 5 but without the leftmost column, because here only pulser signals are used. Turn on the pulser and adjust its height and the gain of each amplifier so that the pulses observed at the unipolar output of the amplifier are about 3.7 volts high, as shown in Figure 6.

![Figure 6: Typical bipolar amplifier output observed with an oscilloscope.](image)

2. Connect the bipolar outputs of the amplifiers to the respective timing SCA inputs.
3. For both SCA modules, turn the upper level control to the maximum value and the lower level control to its minimum value.
4. Connect the oscilloscope to the positive outputs of both SCA modules.
5. Observe the 5V logic pulse output of the SCA and slowly increase the lower level control until the signal suddenly disappears. Note this knob reading and turn the knob to a value 0.1 V (100/1000 div) smaller than the noted reading.
6. Continue to observe the same output and slowly decrease the value in the upper level control until the signal disappears again. Note this knob reading and turn the knob to a value 0.1 V (100/1000 div) larger than the noted reading.
7. Repeat steps 4 to 6 for the other SCA.
8. Set the delay on each SCA to minimum (100 nanoseconds). Feed the fast negative output of the SCA from the 2x2 inch detector to the “start” connector of the TAC, and the other one to the “stop” connector. Set the TAC at a full-scale time range of 500 nsec. The gate should be in anticoincidence.
9. Connect the scope to the TAC output. Adjust the delay on the Stop circuit SCA until the output pulses from the TAC are about 6 volts. Connect this signal to the MCA input and collect a spectrum of these pulses. Record the channel number of the peak and determine the number of counts in the peak for a 5 minute run. Also record the full width at half maximum of the peak (FWHM).
10. Repeat this measurement for different settings of the stop SCA delay (200, 250, 300 and 350 nanoseconds.) Use the oscilloscope to measure the delay accurately.
11. Make a plot of delay (y axis) versus the channel number of the peak in the TAC. The slope of the curve is the calibration in nanoseconds/channel for the TAC settings. In order to measure the time resolution of the pulser peak, multiply the FWHM of the peak by the slope of the delay versus pulse height curve. This calculation should be done for each pulser peak that is observed.

III  **Lifetime measurement of the 14.4 keV state in $^{57}$Fe**

**Procedures**

Set up the electronics as shown in figure 5. The 905-3 2x2 inch NaI (TI) detector will be used to detect the $\gamma_2$ events at 122 keV and to start a time measurement for each sensed event. The other thin window NaI (TI) detector will be used to detect the $\gamma_1$ events at 14.41 keV and to stop the time measurements.

1. Turn on the high voltage power supply to 1000 volts for each detector.

2. Reset both SCA lower level controls to 0, the upper level to maximum and the delay to minimum.

3. Set the gain of both amplifiers to the recommended values shown on the apparatus.

4. Connect the unipolar output of the amplifier (from the 2x2 inch detector) to the MCA and collect a gamma spectrum for the 122 keV and 136 keV energies.

5. Take note of the channel number, $X_1$, at the valley which lies between the 122 keV photopeaks and the Compton edge. Also note the other channel, $X_2$, at the end of the 136 keV line.

6. Switch off the high voltage supply and use the pulser to set the window of the SCA for this START circuit.
   The lower level threshold will be set at $X_1$ while the upper level threshold will be set at $X_2$.

7. Next, connect the MCA to the output of the other amplifier and collect a gamma spectrum for the 14.4 keV peak. Note the channels before and after the photopeak as these will be used to set the lower and upper threshold for the other SCA.

8. Switch off the high voltage and use the pulser to set the window of this SCA for the STOP circuit.

9. Set the delay of the Start circuit to be 100ns and the delay of the Stop circuit to be 200ns.

10. Turn on the high voltage supply, switch off the pulser and connect the TAC output to the MCA.

11. Accumulate a spectrum for > 15 hours.

12. Save the spectrum as an “ASCII” file.

13. Use EXCEL to open the file and process the data.
Figure 7 shows the results of a typical measurement that was made for this experiment. In order to smooth out the distribution, groups of ten channels were averaged and plotted. The slope of the delay versus channel number for Figure 7 was 0.73 ns/channel. The lifetime of the state is therefore the product of the number of channels for half intensity times the 0.73 ns/channel. Using the data presented in Figure 7, we obtain a lifetime of ~95 ns, which is quite close to the accepted value of 98 ns.

![Figure 7: Mean lifetime calculation](image)