Lab 8: Semiconductor Detectors

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Station 1
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Using the MCA

1. For each conversion gain, calculate the voltage width per channel.

In[1]:=
```
conversionGains = Table[2^n, {n, 8, 14}]
```

Out[1]=
```
{256, 512, 1024, 2048, 4096, 8192, 16 384}
```

According to the spec sheet for the Ortex ASPEC-927 MCA (http://www.ortec-online.com/products/electronics/multichannel-analyzers-mca/basic-analog/aspec-927), the voltage range for our MCA is 0-10V.

In[2]:=
```
voltageWidthPerChannel = 10 / conversionGains // N
```

Out[2]=
```
{0.0390625, 0.0195313, 0.00976563, 0.00488281, 0.00244141, 0.0012207, 0.000610352}
```

The voltage per channel for the various settings of the Conversion Gain parameter are in the table below:

In[3]:=
```
TableForm[Multicolumn[Join[conversionGains, voltageWidthPerChannel], 2] // First,
 TableHeadings → {None, {"Conversion Gain", "Voltage width per Channel"}}]
```

Out[3]//TableForm=

Conversion Gain	Voltage width per Channel
256	0.0390625
512	0.0195313
1024	0.00976563
2048	0.00488281
4096	0.00244141
8192	0.0012207
16 384	0.000610352

2. Using the conversions from 1, determine the voltage measured by the MCA for the determined channel peak number for each of the four conversion gains.

In[4]:=
```
peaks = {324, 2430, 648, 1298};
conversionGains = {512, 4096, 1024, 2048};
voltPeaks = peaks * 10 / conversionGains // N
```

Out[6]= {6.32813, 5.93262, 6.32813, 6.33789}

In[7]:=
```
Mean[voltPeaks]
Mean[{voltPeaks[[1]], voltPeaks[[3]], voltPeaks[[4]]}]
StandardDeviation[voltPeaks]
(Mean[voltPeaks] - voltPeaks[[2]]) / StandardDeviation[voltPeaks]
```

Out[7]= 6.23169

Out[8]= 6.33138

Out[9]= 0.199435

Out[10]= 1.4996

The peak channel on the MCA software corresponded to a voltage of 6.23V, or 6.33V if the outlier (conversion gain of 4096, approximately 1.5σ below the mean value) is excluded. Error analysis was not conducted as no uncertainty in the 10V max was provided by the MCA manufacturer and the error in the number of bits in the address space was assumed to be zero.

It is assumed that, as the 4096 channel data were collected first while the other settings were collected in rapid

3. From the data recorded, make a properly formatted table of the data (conversion gain, peak channel number, and voltage corresponding to the channel peak number).

In[11]:=
```
TableForm[Multicolumn[Join[conversionGains, peaks, voltPeaks], 3] // First,
 TableHeadings → {None, {"Conversion Gain", "Peak Channel", "Peak Voltage"}}]
```

Out[11]//TableForm=

Conversion Gain	Peak Channel	Peak Voltage
512	324	6.32813
4096	2430	5.93262
1024	648	6.32813
2048	1298	6.33789

4. From the data in the table and **in a text-style cell**, discuss the trends seen in the peak channel number and corresponding voltage to the peak channel number. Which one is constant and which one changes?

Why does that one change? Does it make sense?

As expected, the peak channel changes while the peak voltage remains constant. Altering the number of channels (bits in the address space) only changes the "binning" when processing the incoming signals. Therefore the size of the voltage range represented by each channel changes, but the input voltage range remains from 0-10V.

MCA Linearity

1. From the spectrum saved (should contain a total of 15 peaks), find the peak channel number (i.e., the average channel number used in a Gaussian fit) for each of the 15 peak regions.

a. **Note:** This can be found by multiplying the number of counts by the channel number, summing up this quantity over the Gaussian region, and then dividing by the total number of counts observed in this region (area of Gaussian).

b. **Note:** This can also be accomplished by fitting a Gaussian to each of the 15 peaks, where the initial guess in the fit can be changed to near the peak of each of the 15 peaks.

In[12]:=
```
datafolder = NotebookDirectory[] <> "data/maestro/Spectra/";
datafile = "thulab8mcalinear.Spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data, 50]
deltaV = 10.0 / ToExpression[
    StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[12]]][[2]]];
```

Out[15]=
```
{{112, 15451}, {336, 12936}, {604, 12252}, {885, 12664}, {1168, 16397},
 {1453, 10244}, {1716, 16110}, {2012, 12512}, {2293, 15461}, {2596, 8738},
 {2831, 15361}, {3126, 13764}, {3386, 9935}, {3680, 10523}, {3885, 9980}}
```

2. For the data in step 1, convert the channel number

to voltage.

In[17]:=
```
voltPeaks = peaks[[ ;; , 1]] * deltaV
```

Out[17]=
```
{0.273504, 0.820513, 1.47497, 2.16117, 2.85226, 3.54823, 4.19048,
 4.91331, 5.59951, 6.33944, 6.91331, 7.6337, 8.26862, 8.98657, 9.48718}
```

In[18]:=
```
TableForm[voltPeaks]
```

Out[18]//TableForm=
```
0.273504
0.820513
1.47497
2.16117
2.85226
3.54823
4.19048
4.91331
5.59951
6.33944
6.91331
7.6337
8.26862
8.98657
9.48718
```

The voltages corresponding to the 15 peaks are printed in table form above.

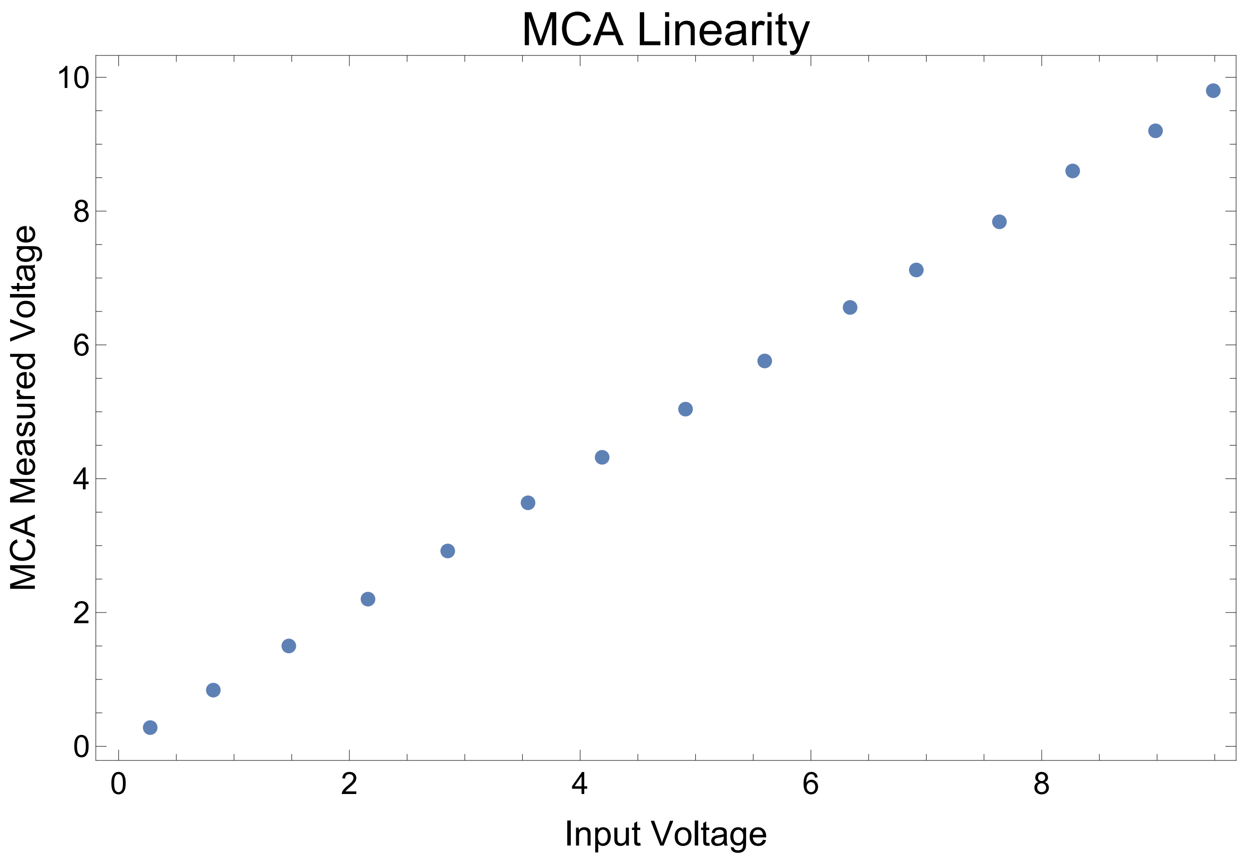
3. From the data in step 2, create a properly formatted plot of MCA measured voltage vs. input voltage (y on x). This is the integral nonlinearity plot of the MCA, similar to figure 2 in the introduction.

In[19]:=
```
measuredpeaks = Sort[{6.56, 0.28, 0.84, 1.50,
   2.20, 2.92, 3.64, 4.32, 5.04, 5.76, 7.12, 7.84, 8.60, 9.20, 9.80}]
```

Out[19]=
```
{0.28, 0.84, 1.5, 2.2, 2.92, 3.64, 4.32, 5.04, 5.76, 6.56, 7.12, 7.84, 8.6, 9.2, 9.8}
```

In[20]:=
```
mcaplot = ListPlot[Multicolumn[Join[voltPeaks, measuredpeaks], 2] // First,
  ImageSize -> Full, Frame → True,
  FrameLabel → {Style["Input Voltage", 18], Style["MCA Measured Voltage", 18]},
  FrameTicksStyle → Directive[Black, 16], PlotLabel → Style["MCA Linearity", 24]]
```

Out[20]=



4. Using equation 1, determine the integral nonlinearity for each of the 15 data points. Place data in a properly formatted table (input voltage, output voltage determined via the Gaussian fit, and integral nonlinearity.

In[21]:=
```
formatnum[list_, fig_, dec_] :=
 Table[NumberForm[list[[i]], {fig, dec}], {i, Length[list]}]
```

In[22]:=
```
equationOne[Vnom_, Vact_, Vmax_] := (Vnom - Vact) * 100 / Vmax;
TableForm[
 Multicolumn[Join[formatnum[measuredpeaks, 4, 2], formatnum[voltPeaks, 4, 2],
    formatnum[equationOne[measuredpeaks, voltPeaks, 10], 4, 2]], 3] // First,
 TableHeadings -> {None, {"Input Voltage (±0.01V)",
    "Measured Peak Voltage (V)", "Integral Nonlinearity (%)"}}]
```

Out[23]//TableForm=

Input Voltage (±0.01V)	Measured Peak Voltage (V)	Integral Nonlinearity (%)
0.28	0.27	0.06
0.84	0.82	0.19
1.50	1.47	0.25
2.20	2.16	0.39
2.92	2.85	0.68
3.64	3.55	0.92
4.32	4.19	1.30
5.04	4.91	1.27
5.76	5.60	1.60
6.56	6.34	2.21
7.12	6.91	2.07
7.84	7.63	2.06
8.60	8.27	3.31
9.20	8.99	2.13
9.80	9.49	3.13

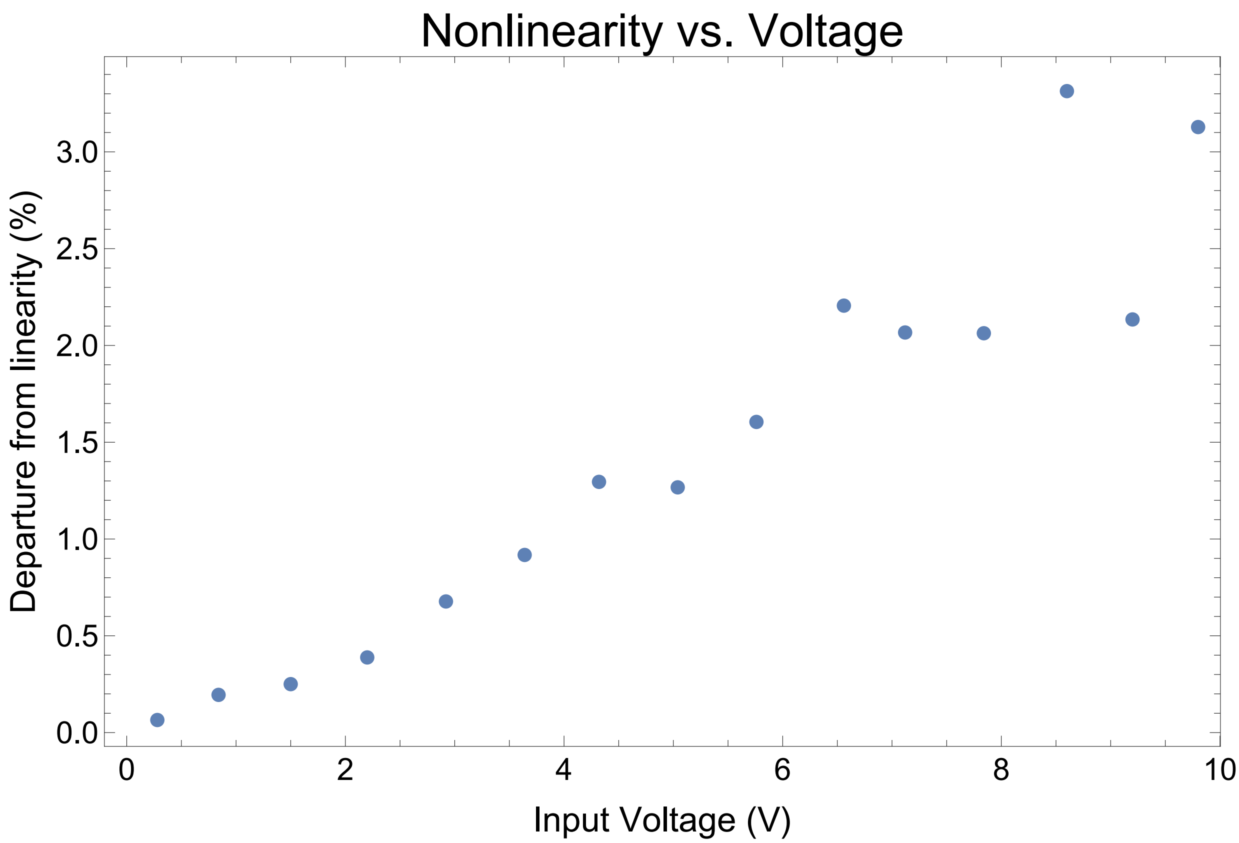
5. Looking at the plot from 3 and data in 4, comment on the integral nonlinearity of the MCA over the input voltage range. Is the integral nonlinearity zero, constant, and/or varying across the voltage range?

In[24]:=
```
line = LinearModelFit[
  Multicolumn[Join[measuredpeaks, equationOne[measuredpeaks, voltPeaks, 10]], 2] //
   First, x, x]
```

Out[24]= FittedModel[$-0.174739 + 0.319935\,x$]

In[25]:=
```
pp = ListPlot[
  Multicolumn[Join[measuredpeaks, equationOne[measuredpeaks, voltPeaks, 10]], 2] //
   First, ImageSize → Full, PlotLabel → Style["Nonlinearity vs. Voltage", 24],
  Frame → True, FrameLabel → {Style["Input Voltage (V)", 18],
    Style["Departure from linearity (%)", 18]}, FrameTicksStyle → Directive[16]]
```

Out[25]=



The integral nonlinearity increases with input voltage. In this range it is not possible to determine whether or not the relationship is approximately linear or if it follows some other curve. Certainly the deviation from a linear value also increased with time, though the inconsistent curve suggests that noise was introduced at a higher magnitude as a function of voltage.

MCA Dead Time

1. From the data collected, make a properly formatted table of the time delay between amplifier output peaks and amplifier output amplitude for the first (larger) amplifier analog signal.

In[26]:=
```
data = {{5.44, 3.72}, {1.08, 3.58}, {3.00, 3.63}, {7.04, 3.73}, {9.00, 3.72}};
TableForm[
 Multicolumn[Join[formatnum[data[[ ;; , 1]], 3, 2], formatnum[data[[ ;; , 2]], 3, 2]],
   2] // First, TableHeadings → {None, {"Voltage (±0.01V)", "Delay (±0.01μs)"}}]
```

Out[27]//TableForm=

Voltage (±0.01V)	Delay (±0.01μs)
5.44	3.72
1.08	3.58
3.00	3.63
7.04	3.73
9.00	3.72

2. From the table of data in step 1, identify if the dead time is a function of input amplitude or not.

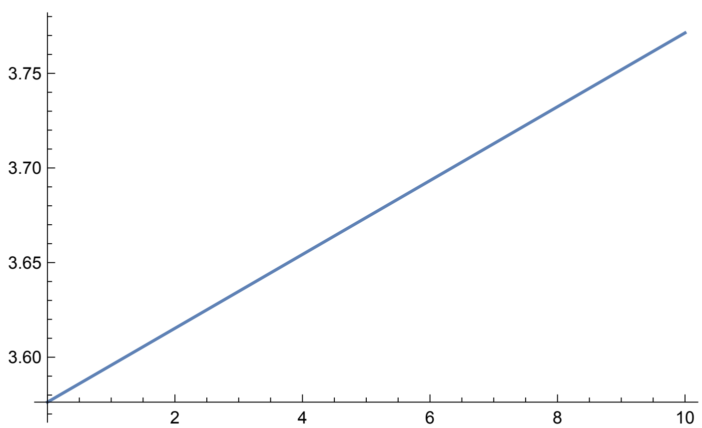
In[28]:=
```
Correlation[data[[ ;; , 1]], data[[ ;; , 2]]]
```

Out[28]= 0.912855

In[29]:=
```
ft = LinearModelFit[data, x, x]
```

Out[29]= FittedModel[3.57625 + 0.0195124 x]

In[30]:=
```
Plot[ft[x], {x, 0, 10}]
ft[0]
ft[10]
```

Out[30]=


Out[31]= 3.57625

Out[32]= 3.77138

From the data it appears that dead time is a function of input amplitude, with the two values 91% correlated. Assuming a linear fit, the deadtime for 0V would be 3.58μs, while the deadtime for 10V would be 3.77μs.

3. **In a text-style cell** and using the introduction of the laboratory assignment for guidance, theorize on

which of the three ADC designs discussed is used by ORTEX in the ASPEC 927 MCA. Justify the choice made.

4. **Insert your answer in the same text-style cell for this answer:** Go online and find the spec sheet of the ORTEC ASPEC 927 MCA. Find the quoted value of the dead time on the spec sheet. Compare the experimental result with that quoted by the manufacturer.

This ADC is a Wilkinson ADC. The Wilkinson design collects charge in a capacitor and compares the resultant voltage to a reference value. When the voltages match, the capacitor is allowed to discharge and this time is counted by a high frequency clock. Since higher energy pulses take longer to discharge, this results in longer deadtimes for higher-energy pulses.

From the specification sheet at http://www.ortec-online.com/products/electronics/multichannel-analyzers-mca/basic-analog/aspec-927, this MCA has a dead time of 2μs (including memory transfer). This is shorter than the measured dead time, which could be a result of error in measurement, or of the precision of the oscilloscope. However, it is unlikely that this could account for the factor of 1.75-1.89 increase in deadtime as measured in the lab. While the manufacturer's specification may represent an ideal case, it is clearly not indicative of real-world values.

Spectroscopy with the HPGe Detector

1. Determine the peak location of each peak of each spectrum. Correspond the channel number to the energy (**keV**) for that source, as found in the pre-laboratory assignment. Provide a table of the data (source name, energy of gamma-ray, channel number of peak for that gamma ray).

Note: organizationally, it made more sense to conduct this analysis for each source independently, rather than in the sequence provided (allowing for employment of repetitive proceses, which is what computers are for).

Due to the presence of background spectra even when the source safe was closed (especially Cs-137), analysis of the non-background-corrected spectra was not conducted. Instead, the peaks were found using spectra with background count rates removed in order to minimize the effects of other sources.

Even with background removed, the station 1 detector was positioned close enough to the safe to render spectral identification difficult if not impossible. Therefore data from station 5 were used as they were comparatively low background.

Part 2 performed below.

3. Correct all collected spectra (including background) to convert the abscissa values (channel number) to voltage [sic] and ordinate values to count rate (divide each channel by the acquisition time).

This is performed below for each source.

4. With the spectra updated for energy, provide a properly-formatted plot of the background spectra collected in the experimental section labeled **Background** as y=**count rate (c/s)** and x=**Energy (either keV or MeV)**.

6. Below each plot students will include calculations and text-style cells to conduct the following analyses.

a. In a text-style cell along with the drawing tools inherent within Mathematica, identify the spectral features of each spectra. This includes the region where background contributes significantly, backscatter, Compton continuum, Compton edge, double Compton scattering region, annihilation peaks, full energy peak, and any X-rays that may be present in the spectrum (low energy lines in the pulse height spectrum).

b. Calculate the energy resolution of each gamma-ray full energy peak present in each spectrum.

Properly comment your code or provide the answer in a text-style cell.

In[33]:=
```
datafolder = NotebookDirectory[] <> "data/maestro/Spectra/efrancis/";
numberofchannels = 2^14;
deltaV = 10 / numberofchannels;
```

Background

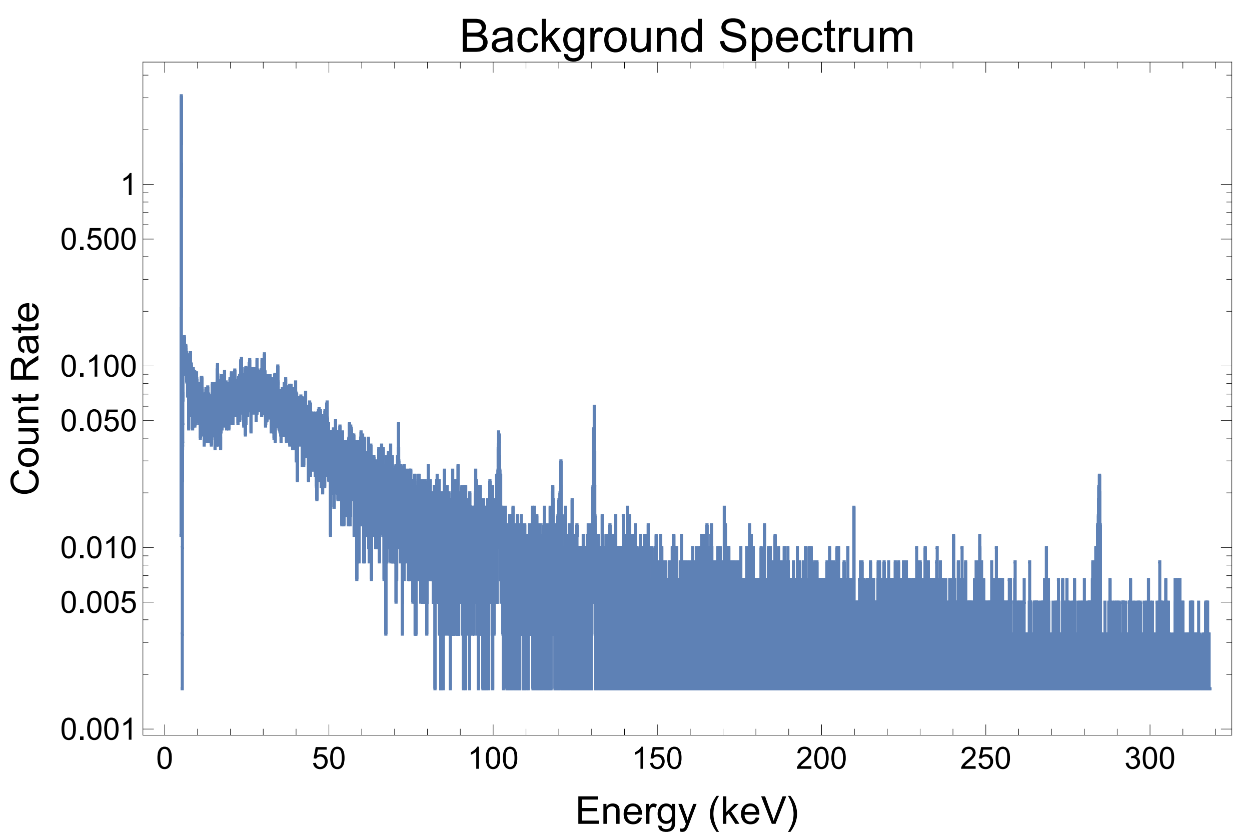
In[36]:=
```
bgtime = 600;
datafile = "bkg.Spe";
bgdata =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[bgdata, 750, 0.5]
energies = {};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
bgratedata = bgdata / bgtime;
channels = Table[ft[x], {x, Length[bgdata]}];
ListLogPlot[Multicolumn[Join[channels, bgratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Background Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

Out[39]= { }

Out[41]//TableForm=

Peak Channel	Energy (keV)
Null	

Out[44]=



Na-22

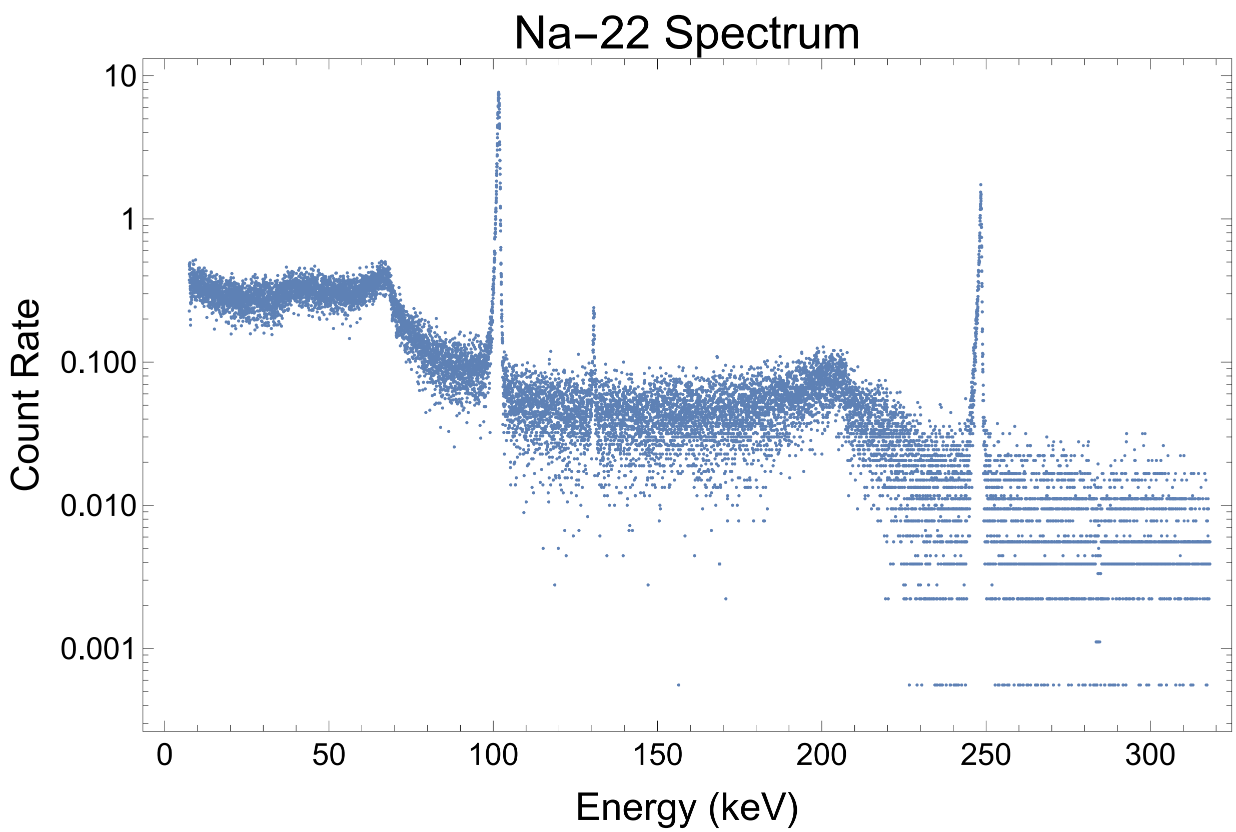
In[45]:=
```
time = 180;
datafile = "na22.spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data / time - bgdata / bgtime, 50, 0.0000005, 1] // N
energies = {511, 1274};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data / time - bgdata / bgtime;
channels = Table[ft[x], {x, Length[data]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Na-22 Spectrum", 24], Joined → False, InterpolationOrder → 0]
```

Out[48]= {{5026., 7.66333}, {12546., 1.73556}}

Out[50]//TableForm=

Peak Channel	Energy (keV)
5026.	511
12546.	1274

Out[53]=



Cs-137

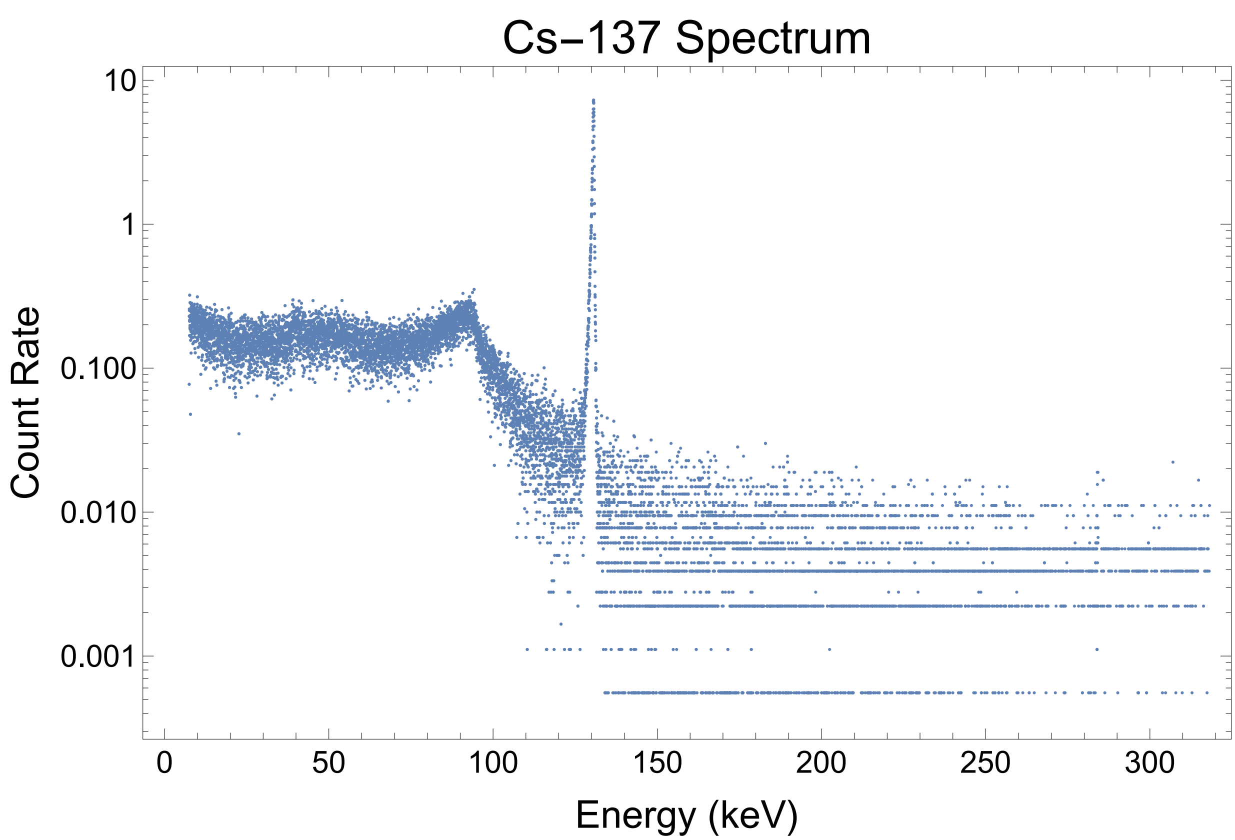
In[54]:=
```
time = 180;
datafile = "Cs137.spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data / time - bgdata / bgtime, 50, 10^-5, 0.5] // N
energies = {661.7};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data / time - bgdata / bgtime;
channels = Table[ft[x], {x, Length[ratedata]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Cs-137 Spectrum", 24], Joined → False, InterpolationOrder → 0]
```

Out[57]= {{6510., 7.27333}}

Out[59]//TableForm=

Peak Channel	Energy (keV)
6510.	661.7

Out[62]=



Co-57

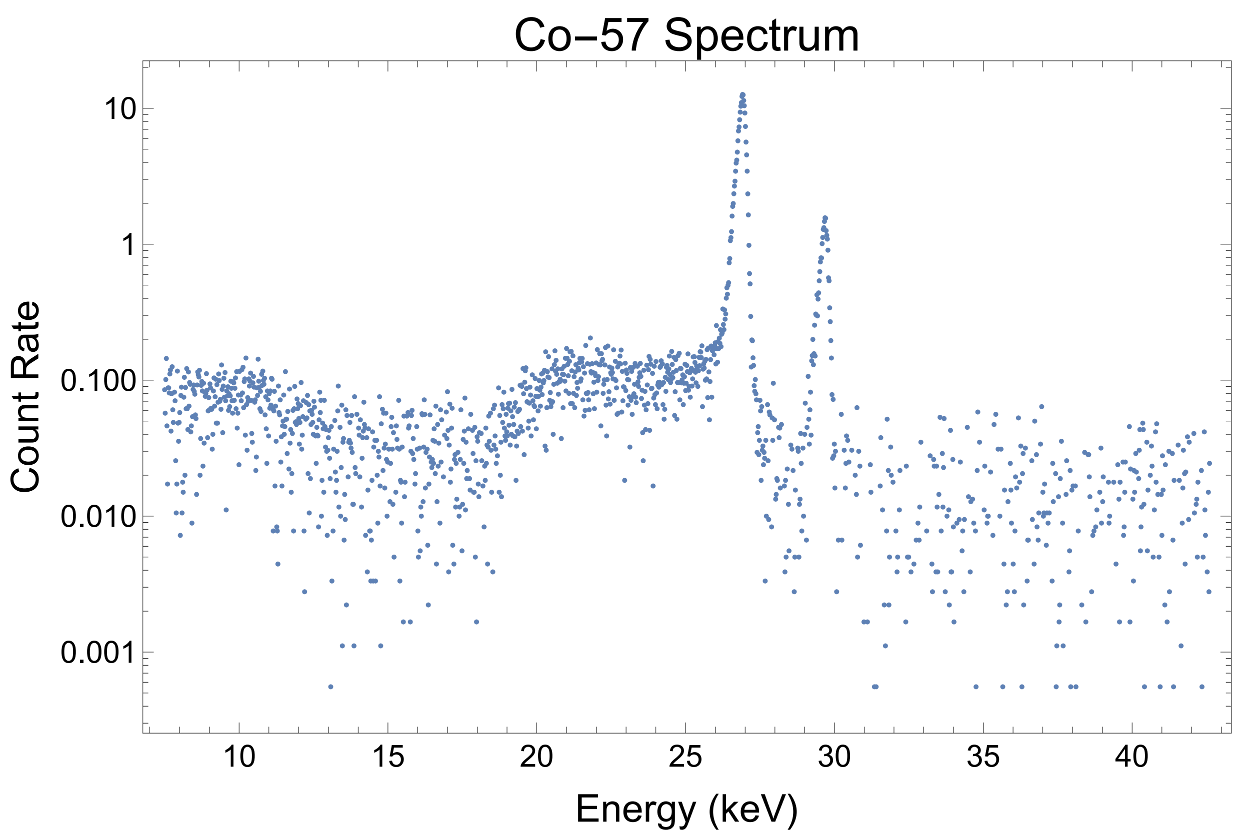
In[63]:=
```
time = 180;
datafile = "Co57.spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data[[ ;; 2000]] / time - bgdata[[ ;; 2000]] / bgtime,
   10, 10^-8, 0.6] // N
energies = {122, 136};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data[[ ;; 2000]] / time - bgdata[[ ;; 2000]] / bgtime;
channels = Table[ft[x], {x, Length[ratedata]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Co-57 Spectrum", 24]]
```

Out[66]= {{1196., 12.6428}, {1338., 1.565}}

Out[68]//TableForm=

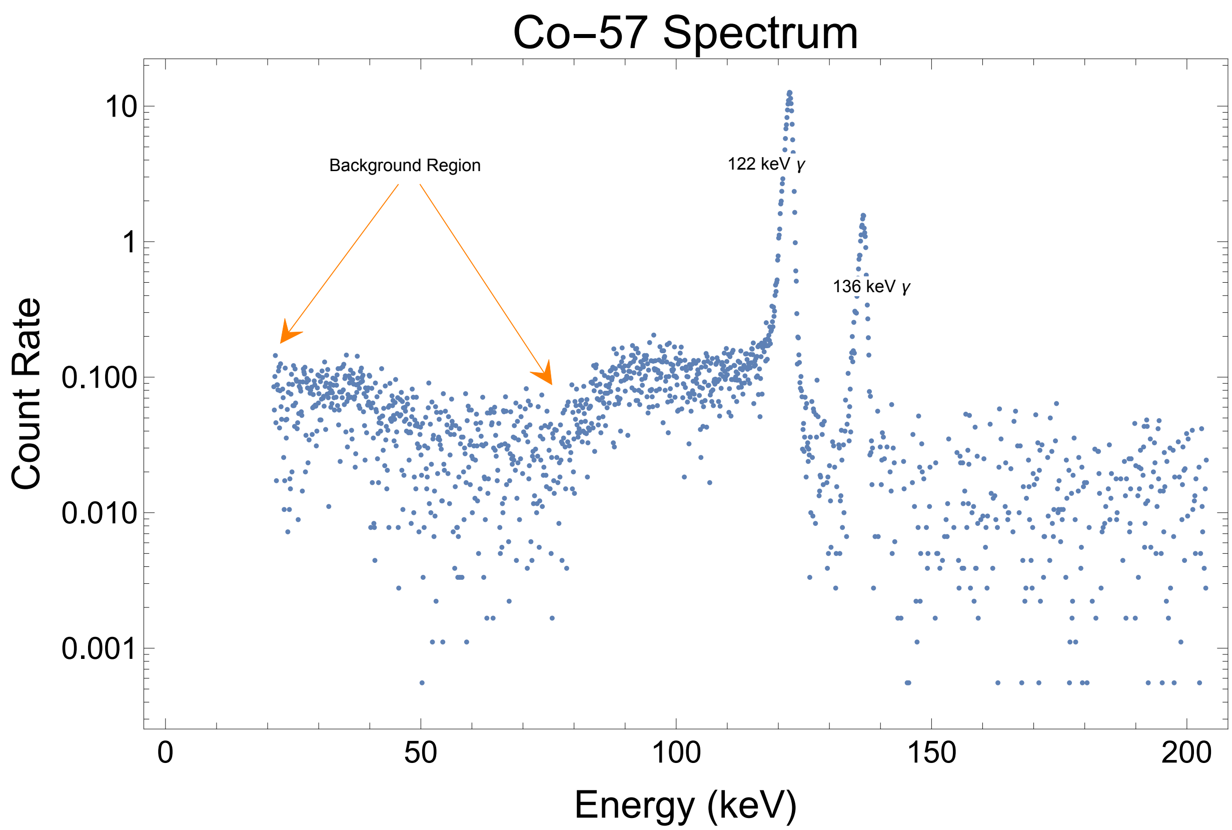
Peak Channel	Energy (keV)
1196.	122
1338.	136

Out[71]=

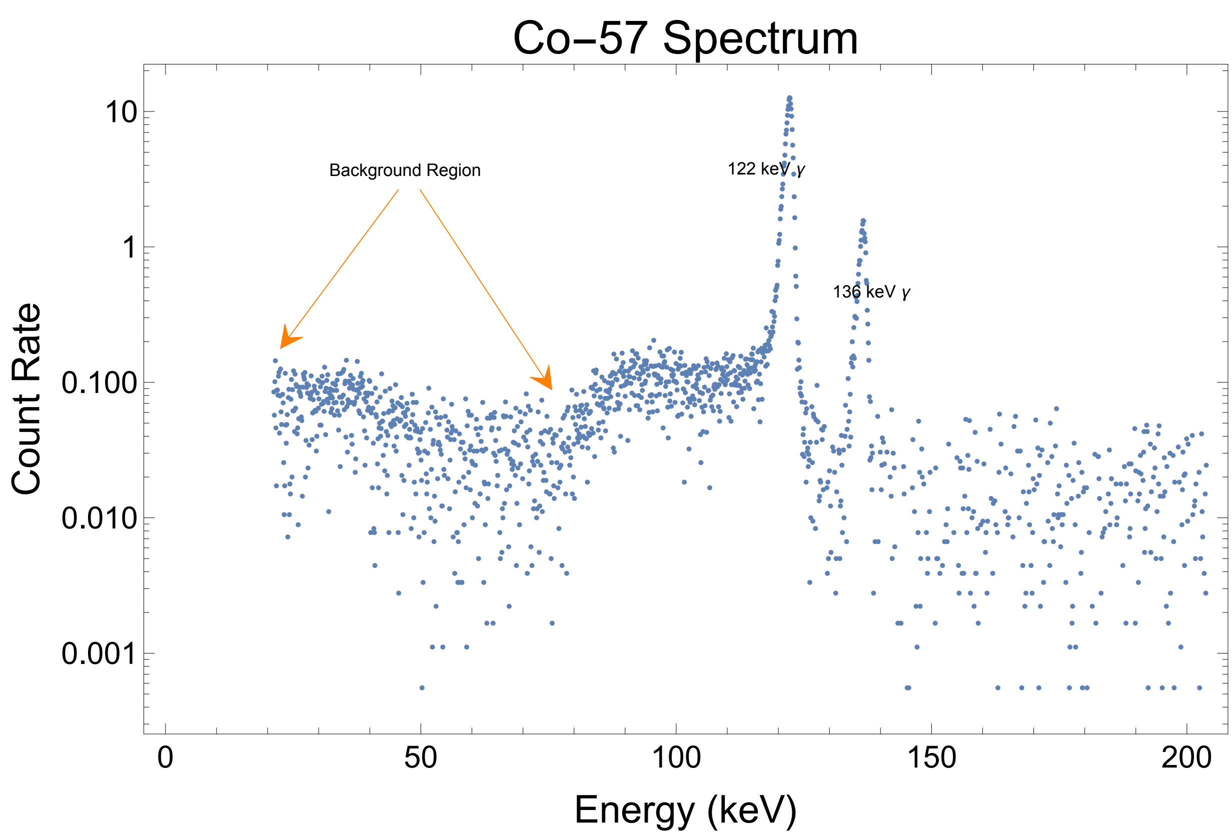


In[72]:=

In[73]:=


Co−57 Spectrum
Background Region
122 keV γ
136 keV γ
Count Rate
10
1
0.100
0.010
0.001
0
50
100
150
200
Energy (keV)

Out[73]=


Co−57 Spectrum
Background Region
122 keV γ
136 keV γ
Count Rate
10
1
0.100
0.010
0.001
0
50
100
150
200
Energy (keV)

Co-60

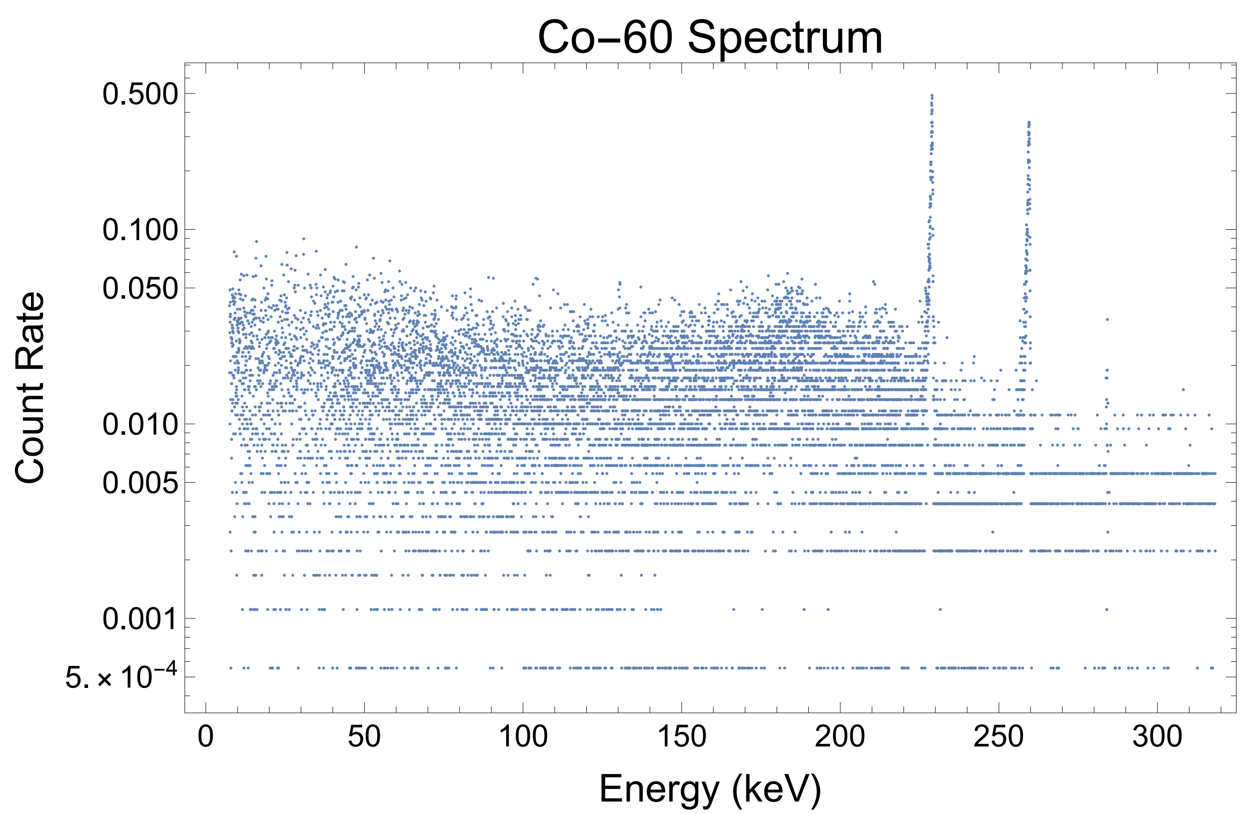
In[74]:=
```
time = 180;
datafile = "Co60.spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data[[10 000 ;;]] / time - bgdata[[10 000 ;;]] / bgtime,
   5, 10^-18, .1] // N
energies = {1173, 1332};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]] + 10 000], Sort[energies]], 2] //
  First, TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data[[ ;; ]] / time - bgdata[[ ;; ]] / bgtime;
channels = Table[ft[x], {x, Length[ratedata]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Co-60 Spectrum", 24]]
```

Out[77]= {{1550., 0.488889}, {3119., 0.355556}}

Out[79]//TableForm=

Peak Channel	Energy (keV)
11 550.	1173
13 119.	1332

Out[82]=



In[83]:=
```
Co60HPGeDeltaV = 10 / Length[data] // N
countsCo60 = data;
```

Out[83]= 0.000610352

In[85]:=
```
10 / 2^14 // N
```

Out[85]= 0.000610352

Ba-133

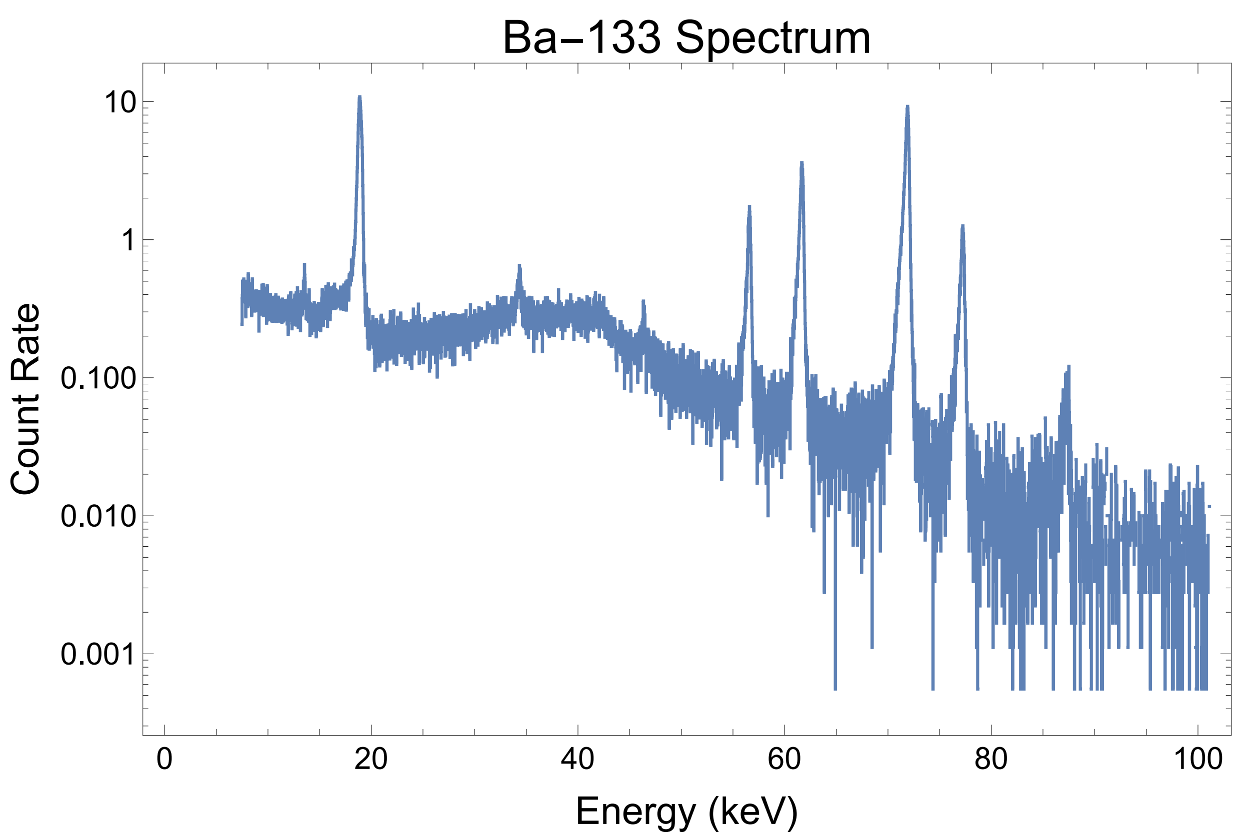
In[86]:=
```
time = 180;
datafile = "Ba133.spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data[[ ;; 5000]] / time - bgdata[[ ;; 5000]] / bgtime, 50, 10^-8, 1] // N
energies = {356, 80.99, 303, 383.851, 276.398};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data[[ ;; 5000]] / time - bgdata[[ ;; 5000]] / bgtime;
channels = Table[ft[x], {x, Length[ratedata]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Ba-133 Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

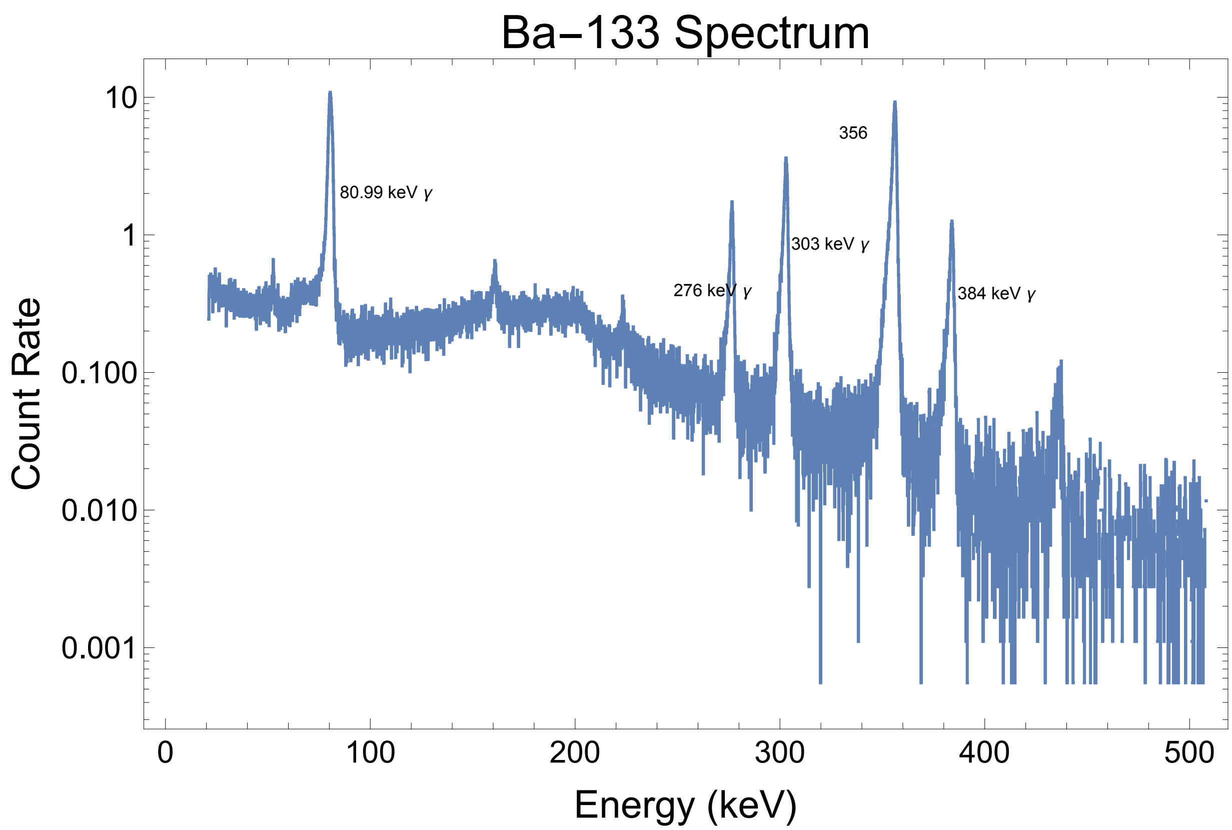
Out[89]= {{784., 10.8617}, {2717., 1.74056}, {2976.5, 3.62}, {3501., 9.24778}, {3775., 1.26}}

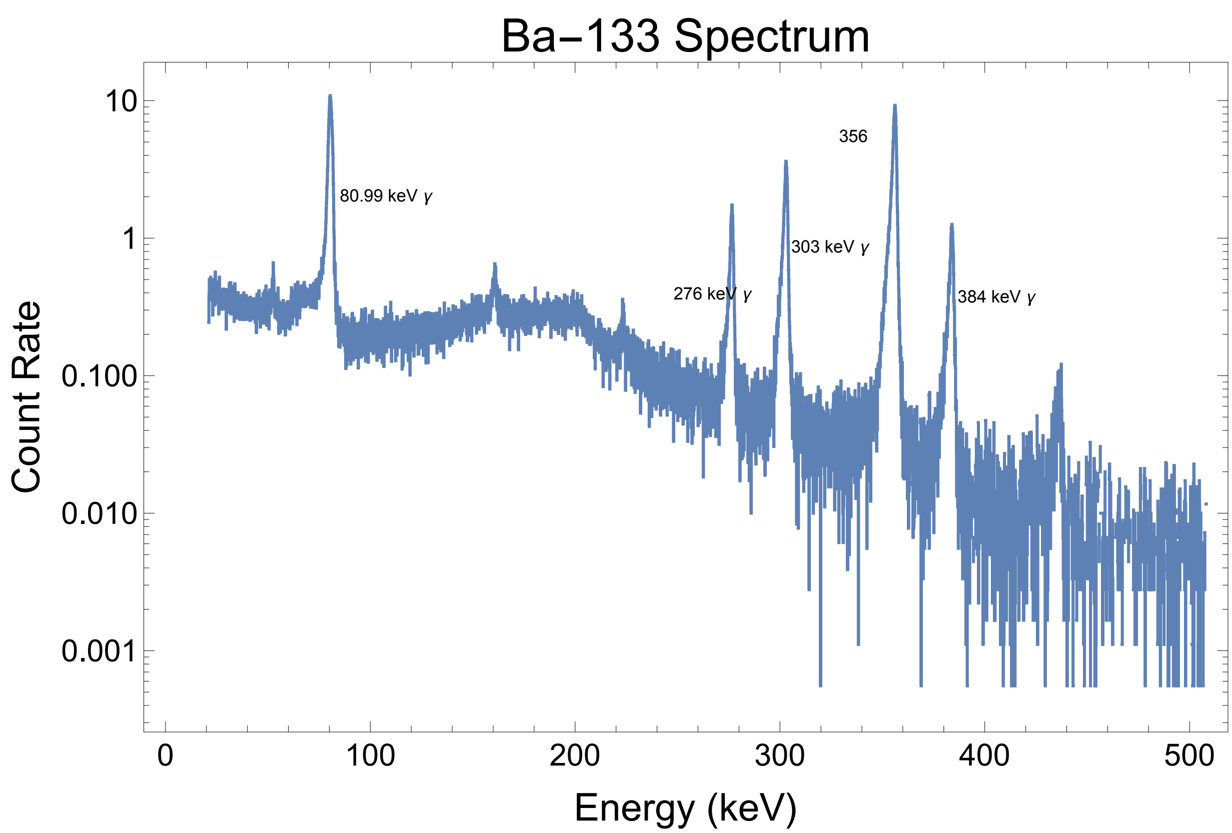
Out[91]//TableForm=

Peak Channel	Energy (keV)
784.	80.99
2717.	276.398
2976.5	303
3501.	356
3775.	383.851

Out[94]=




Ba−133 Spectrum
Count Rate
Energy (keV)
10
1
0.100
0.010
0.001
0
100
200
300
400
500
80.99 keV γ
276 keV γ
303 keV γ
356
384 keV γ


Ba−133 Spectrum
Count Rate
Energy (keV)
10
1
0.100
0.010
0.001
0
100
200
300
400
500
80.99 keV γ
276 keV γ
303 keV γ
356
384 keV γ

Cd-109

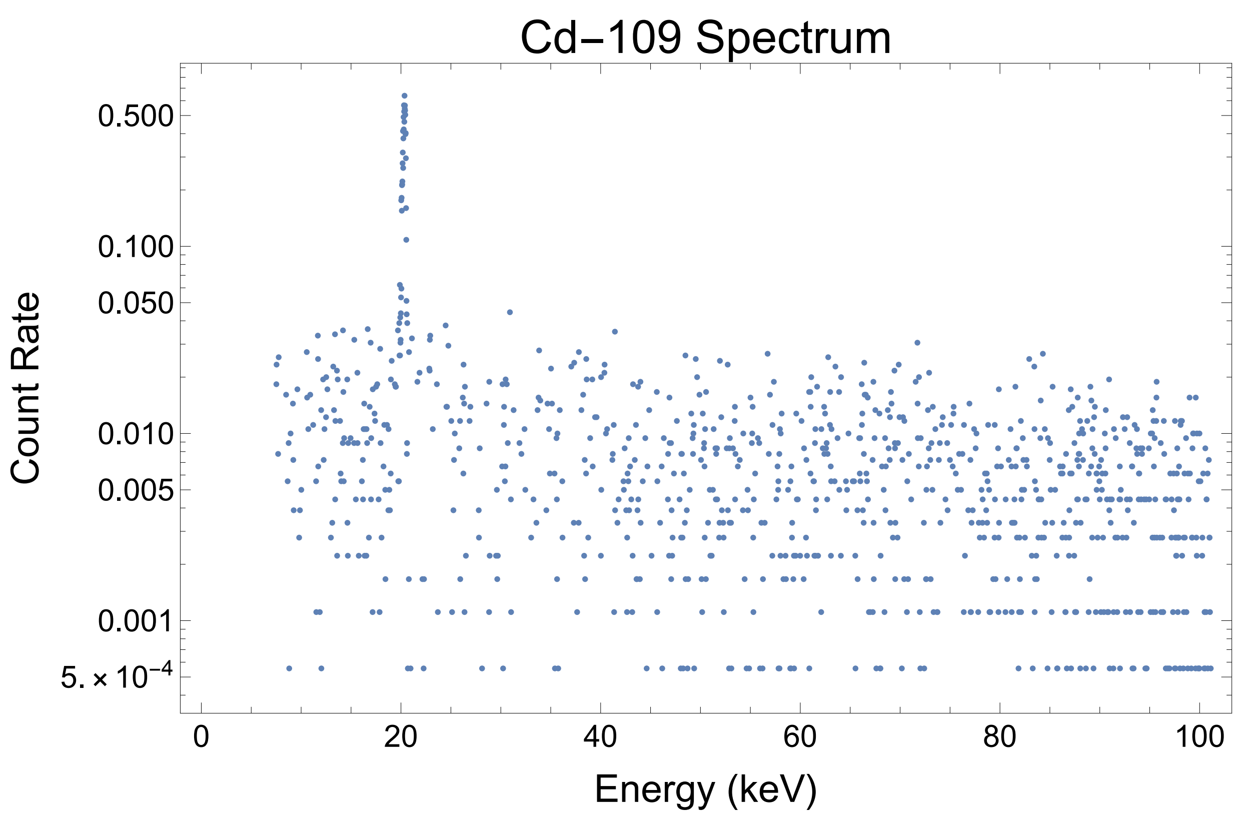
In[95]:=
```
time = 180;
datafile = "Cd109.spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data[[ ;; 5000]] / time - bgdata[[ ;; 5000]] / bgtime,
   50, 10^-8, 0.1] // N
energies = {88.04};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data[[ ;; 5000]] / time - bgdata[[ ;; 5000]] / bgtime;
channels = Table[ft[x], {x, Length[ratedata]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Cd-109 Spectrum", 24]]
```

Out[98]= {{860., 0.637778}}

Out[100]//TableForm=

Peak Channel	Energy (keV)
860.	88.04

Out[103]=



Mn-54

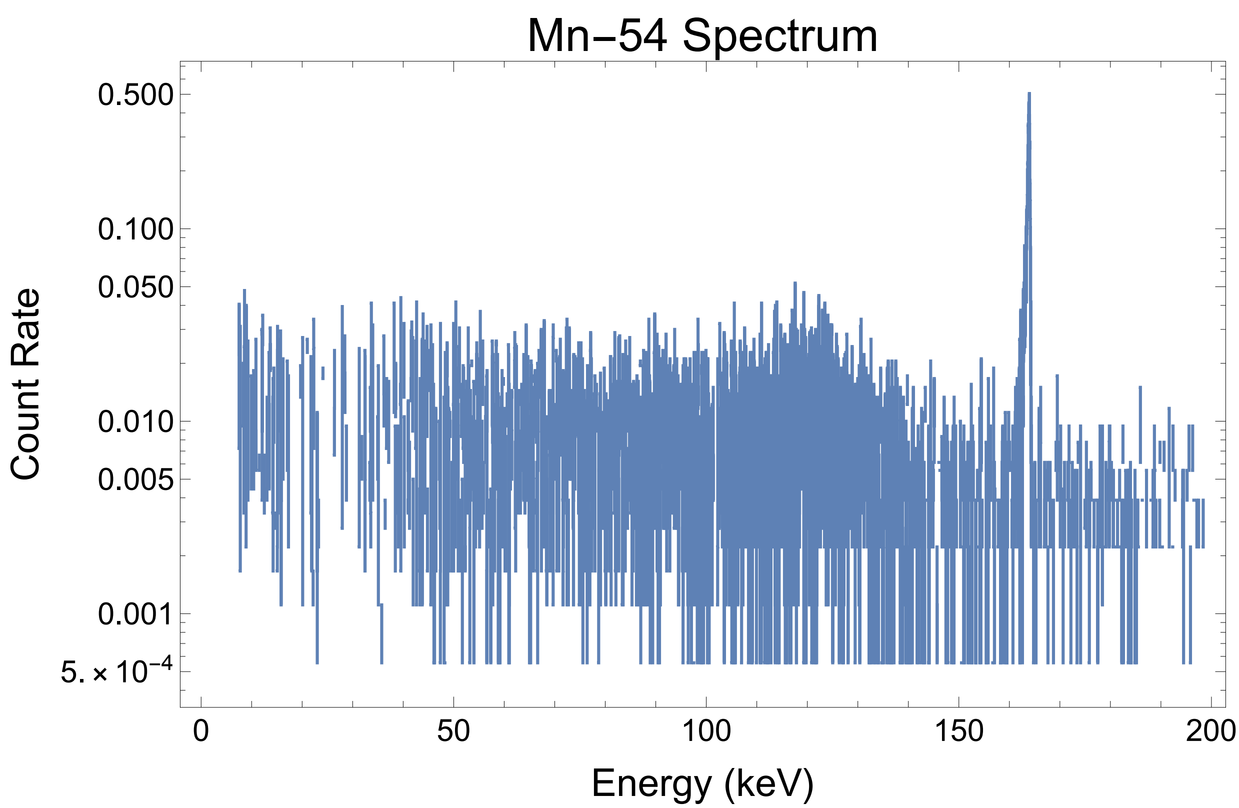
In[104]:=
```
time = 180;
datafile = "Mn54.spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
peaks = FindPeaks[data[[ ;; 10 000]] / time - bgdata[[ ;; 10 000]] / bgtime,
   50, 10^-8, 0.1] // N
energies = {835};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data[[ ;; 10 000]] / time - bgdata[[ ;; 10 000]] / bgtime;
channels = Table[ft[x], {x, Length[ratedata]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Energy (keV)", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Mn-54 Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

Out[107]= {{8214., 0.450556}}

Out[109]//TableForm=

Peak Channel	Energy (keV)
8214.	835

Out[112]=



In[113]:=
```
peakdata = {
    {"Na-22", 511, 5026},
    {"Na-22", 1274, 12 546},
    {"Cs-137", 661.7, 6510},
    {"Co-57", 122, 1196},
    {"Co-57", 136, 1338},
    {"Co-60", 1173, 11 550},
    {"Co-60", 1332, 13 119},
    {"Ba-133", 80.99, 784},
    {"Ba-133", 276.4, 2717},
    {"Ba-133", 303, 2977},
    {"Ba-133", 356, 3501},
    {"Ba-133", 384, 3775},
    {"Cd-109", 88.04, 860},
    {"Mn-54", 835, 8214}
  };
```

In[114]:=
```
TableForm[peakdata,
 TableHeadings → {None, {"Isotope", "Energy (keV)", "Channel No."}}]
```

Out[114]//TableForm=

Isotope	Energy (keV)	Channel No.
Na-22	511	5026
Na-22	1274	12 546
Cs-137	661.7	6510
Co-57	122	1196
Co-57	136	1338
Co-60	1173	11 550
Co-60	1332	13 119
Ba-133	80.99	784
Ba-133	276.4	2717
Ba-133	303	2977
Ba-133	356	3501
Ba-133	384	3775
Cd-109	88.04	860
Mn-54	835	8214

2. Using the data from 1, conduct a linear fit that will give you the best estimate for the conversion of voltage to channel number (that is, the slope in units of V/ch #). Report your answer below the calculations in a text-style cell.

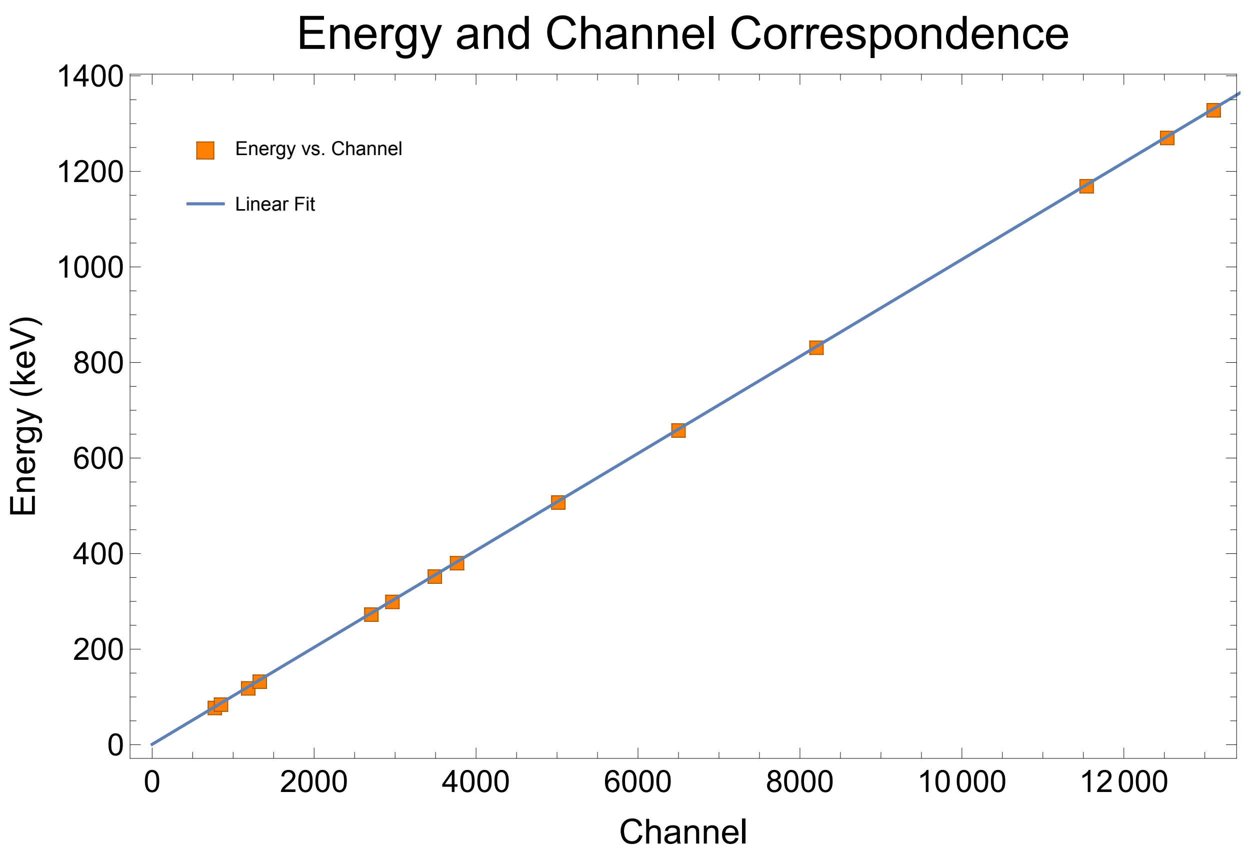
Based on the following questions in the lab report, I have interpreted this as “Energy per channel” rather than V/ch #. As these two should be proportional, this should be transparent, but it will allow the analysis in part 1 to be used here.

In[115]:=
```
ft = LinearModelFit[
  Multicolumn[Join[peakdata[[ ;; , 3]], peakdata[[ ;; , 2]]], 2] // First, x, x]
```

Out[115]=
```
FittedModel[ 0.814812+0.10149 x ]
```

In[116]:=
```
lp = ListPlot[Multicolumn[Join[peakdata[[ ;; , 3]], peakdata[[ ;; , 2]]], 2] // First,
    PlotMarkers → Style[Orange],
    Frame → True, FrameLabel → {Style["Channel", 18], Style["Energy (keV)", 18]},
    ImageSize → Full, PlotLabel → Style["Energy and Channel Correspondence", 24],
    FrameTicksStyle → Directive[16],
    PlotLegends → Placed[{"Energy vs. Channel"}, {0.15, 0.85}]];
pp = Plot[ft[x], {x, 0, 2^14}, PlotLegends → Placed[{"Linear Fit"}, {0.15, 0.85}]];
Show[lp, pp]
```

Out[118]=



6.b. Calculate the energy resolution of each gamma-ray full energy peak present in each spectrum, the area under that peak, and the area under the entire spectrum. Properly comment your code or provide the answer in a text-style cell.

“Calculate” seems like strong word. The process I would have gone through, had I infinite time, would be to determine the amplitude of the peak above the background level, calculate half of this value, then find the two points at which a gaussian fit intersected this half value. This would gve me the full width, half max. Alternatively I could use the standard deviation value from a gaussian fit and used the equation $R = \frac{2\sqrt{2\ln(2)}}{V/\sigma}$. Each of these requires a gaussian fit, which I can’t figure out how to do.

7. Below all of the plots, calculate the photopeak efficiency by a taking the ratio of the area of the photopeak to the area of the entire (background-corrected) spectrum. Provide the data in a properly formatted table (source, gamma-ray energy, area of photopeak, area of entire spectrum, photopeak efficiency).

I was not able to figure out how to use Mathematica (which is terrible) to measure the area under the curve, in spite of its many poorly documented numerical integration claims. I know Python pretty well; I know for sure I could have done it there. I’m pretty sure I could have done it in Excel. I would even have used MatLab for the first time to do this, because why not?

Count Rate

1. Plot each spectrum on a single plot with a legend to correlate each spectra with the source-detector separation distance (counts vs. energy).

a. **Note:** You do not need to background correct these spectra.

b. **Note:** Each trace should have a defining difference to correlate with the legend, such as different colors and/or/features (e.g. solid, dashed, dotted, etc.).

In[119]:=
```
datadir = NotebookDirectory[] <> "data/maestro/Spectra/"
```

Out[119]=
```
/Users/jrpowers-luhn/nucnotes/ne550/Lab 8/data/maestro/Spectra/
```

In[120]:=
```
heights = {0, 2.6, 6.2, 9.4, 11.5, 14.7}(*cm*);
filenames = {
   "lab83Cs0cm.Spe",
"lab83Cs11.5cm.Spe",
"lab83Cs14.7.Spe",
"lab83Cs2.6cm.Spe",
"lab83Cs6.2cm.Spe",
"lab83Cs9.4cm.Spe"
};
```

In[122]:=
```
importData[filename_] :=
 ToExpression[StringSplit[Import[datadir <> filename], "\n"][[13 ;; -15]]]
```

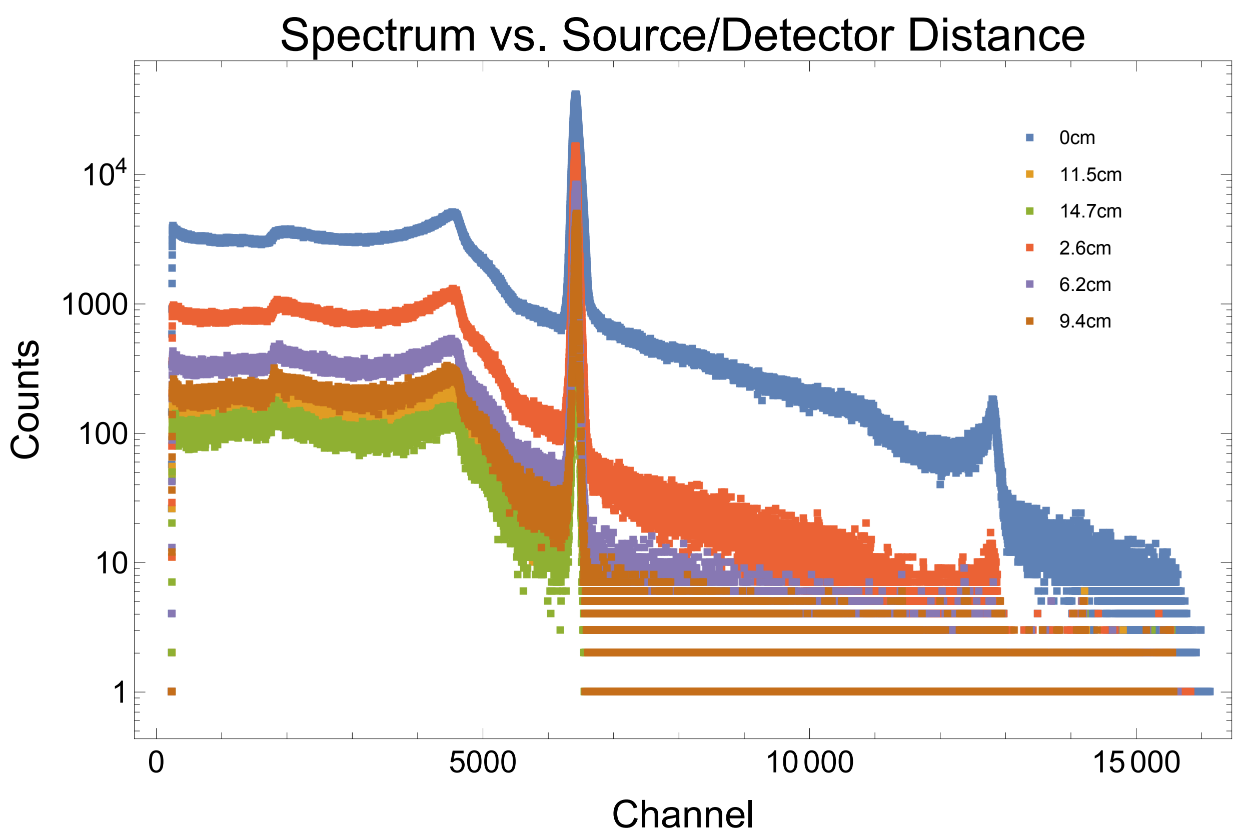
In[123]:=
```
datadir <> "lab83Cs2.6cm.Spe"
```

Out[123]=
```
/Users/jrpowers-luhn/nucnotes/ne550/Lab 8/data/maestro/Spectra/lab83Cs2.6cm.Spe
```

In[124]:=
```
ToExpression[StringSplit[Import[datadir <> "lab83Cs2.6cm.Spe"], "\n"][[13 ;; -15]]];
```

In[125]:=
```
ListLogPlot[Map[importData, filenames], ImageSize → Full, Frame -> True, PlotLegends →
   Placed[{"0cm", "11.5cm", "14.7cm", "2.6cm", "6.2cm", "9.4cm"}, {0.85, 0.75}],
 PlotLabel → Style["Spectrum vs. Source/Detector Distance", 24],
 FrameLabel → {Style["Channel", 20], Style["Counts", 20]},
 FrameTicksStyle → Directive[16], PlotMarkers → Style["■", Small]]
```

Out[125]=



2. Referring to the plot from 1, explain the trends seen.

The peak remains prominent, even at larger distances. As distances grow smaller, however, the other source information grows disproportionately. As a result, the Compton edges are more clearly visible in the 0cm plot than in the 14.7cm plot. Not captured in this plot is the fact that the channel errors are significantly lower for the closer sources, and that the dead time is higher.

CZT Detector

1. Repeat the entire data processing conducted with the HPGe detector data with the CZT Detector data.

a. **Note:** Ensure that a clear separation is provided in the Mathematica notebook so the GTAs know when you started this section of the post-laboratory analysis.

In[126]:=
```
datafolder = NotebookDirectory[] <> "data/czt/"
```

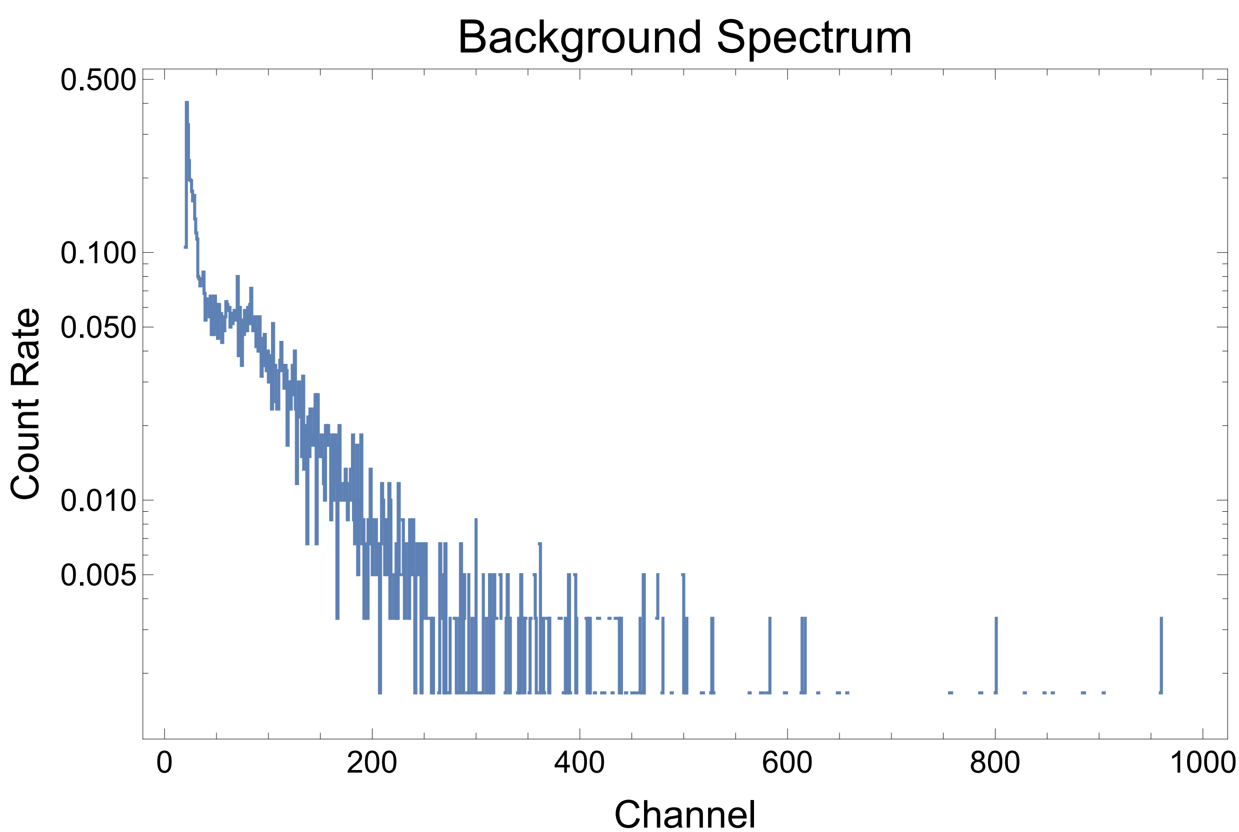
Out[126]=
```
/Users/jrpowers-luhn/nucnotes/ne550/Lab 8/data/czt/
```

Background

```
In[127]:= datafile = "Background_600sec.Spe";
bgdata =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
bgtime = ToExpression[
   StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[10]]][[1]]];
peaks = FindPeaks[bgdata, 750, 0.5]
energies = {};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
bgratedata = bgdata / bgtime;
channels = Table[x, {x, Length[bgdata]}];
ListLogPlot[Multicolumn[Join[channels, bgratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Channel", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Background Spectrum", 24], Joined → True, InterpolationOrder → 0]

Out[130]= { }

Out[132]//TableForm=
```

Peak Channel	Energy (keV)
Null	

Out[135]=



Na-22

In[136]:=
```
datafile = "Na_22_300sec.Spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -16]]];
time = ToExpression[
  StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[10]]][[1]]]
peaks = {{375, 0}}
energies = {511};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data / time - bgdata / bgtime;
channels = Table[x, {x, Length[ratedata]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Channel", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Na-22 Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

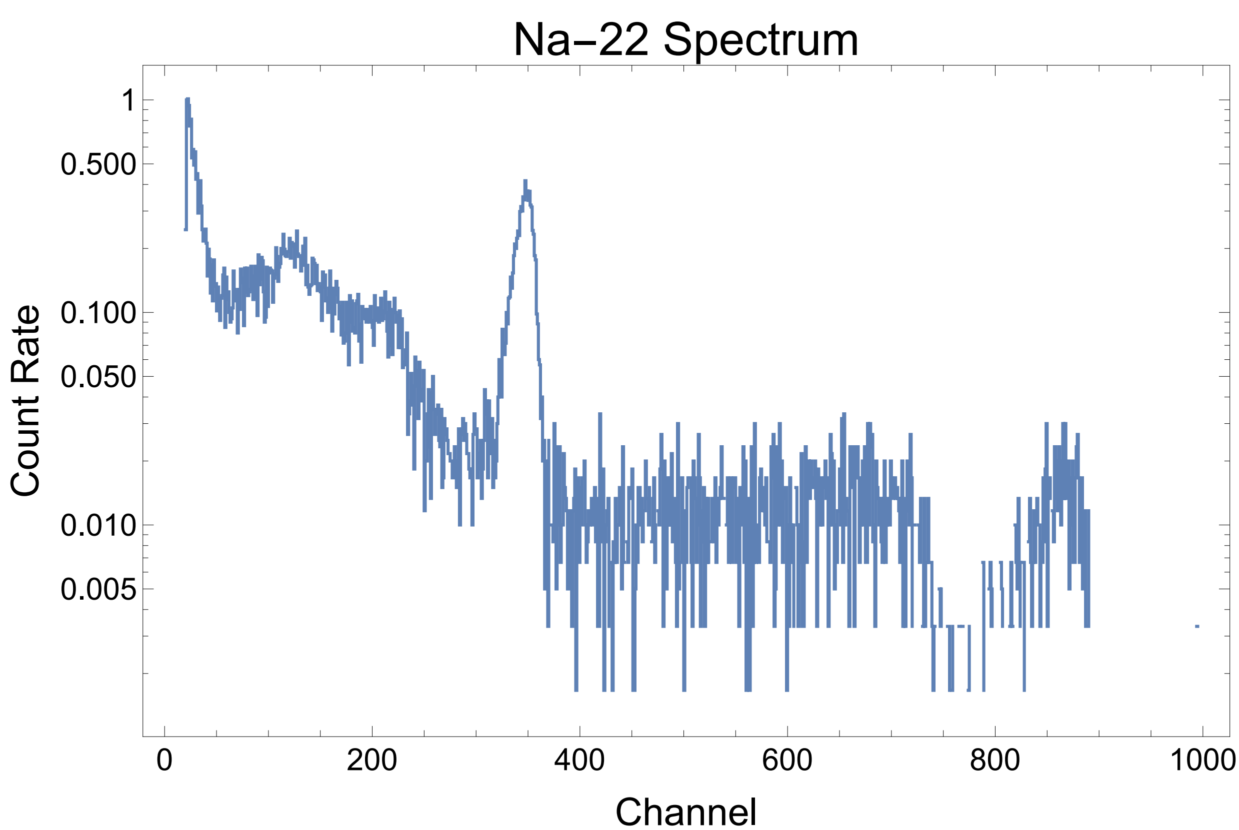
Out[138]= 300

Out[139]= {{375, 0}}

Out[141]//TableForm=

Peak Channel	Energy (keV)
375	511

Out[144]=



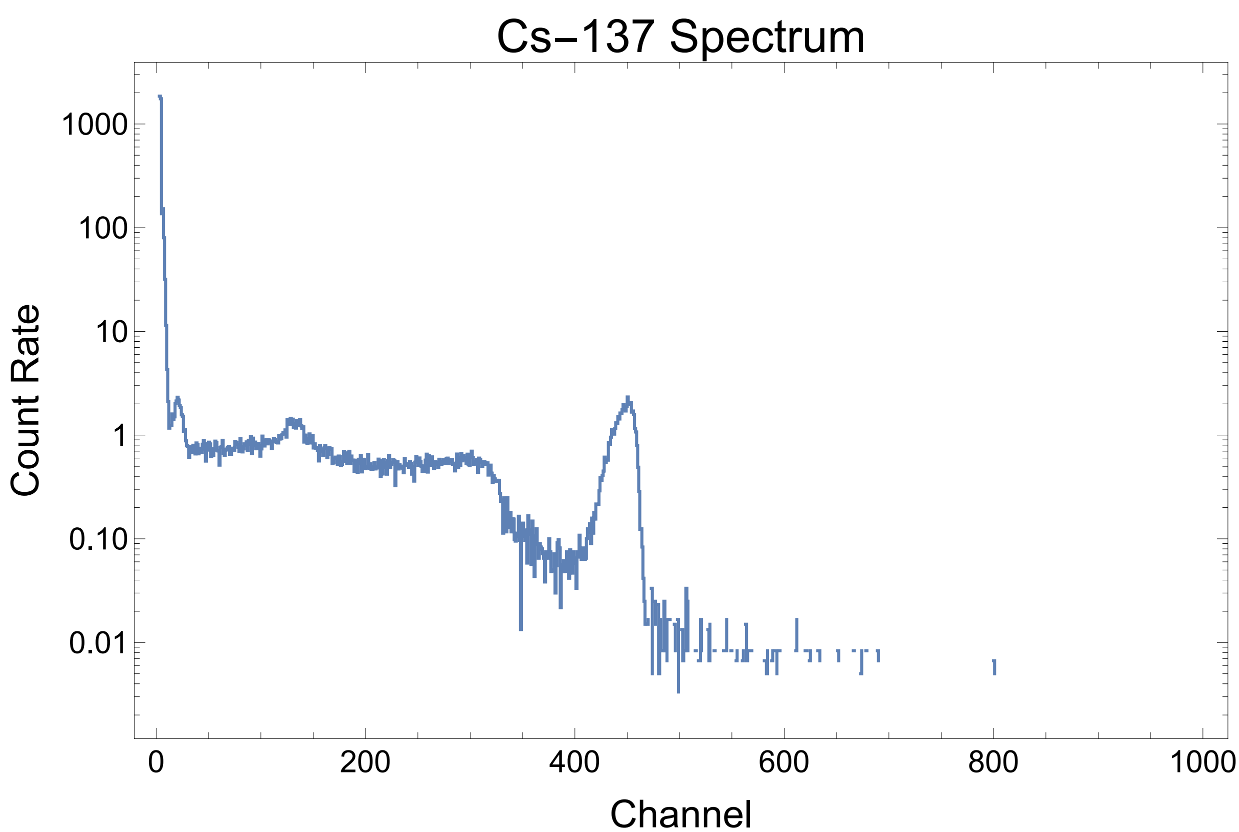
Cs-137

```
In[145]:= datafile = "Cs_137_120sec.Spe";
          data =
            ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -16]]];
          time = ToExpression[
            StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[10]]][[1]]]
          peaks = {{400, 0}}
          energies = {835};
          TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
           TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
          ratedata = data / time - bgdata / bgtime;
          channels = Table[x, {x, Length[data]}];
          ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
           Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
           FrameLabel → {Style["Channel", 20], Style["Count Rate", 20]},
           PlotLabel → Style["Cs-137 Spectrum", 24], Joined → True, InterpolationOrder → 0]

Out[147]= 120

Out[148]= {{400, 0}}
```

Out[150]//TableForm=

Peak Channel	Energy (keV)
400	835

Out[153]=



Co-60

In[154]:=
```
datafile = "Co_60_600sec.Spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
time = ToExpression[
  StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[10]]][[1]]]
peaks = {{800, 0}, {910, 0}}
energies = {1173, 1332};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data / time - bgdata / bgtime;
channels = Table[x, {x, Length[data]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Channel", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Co-60 Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

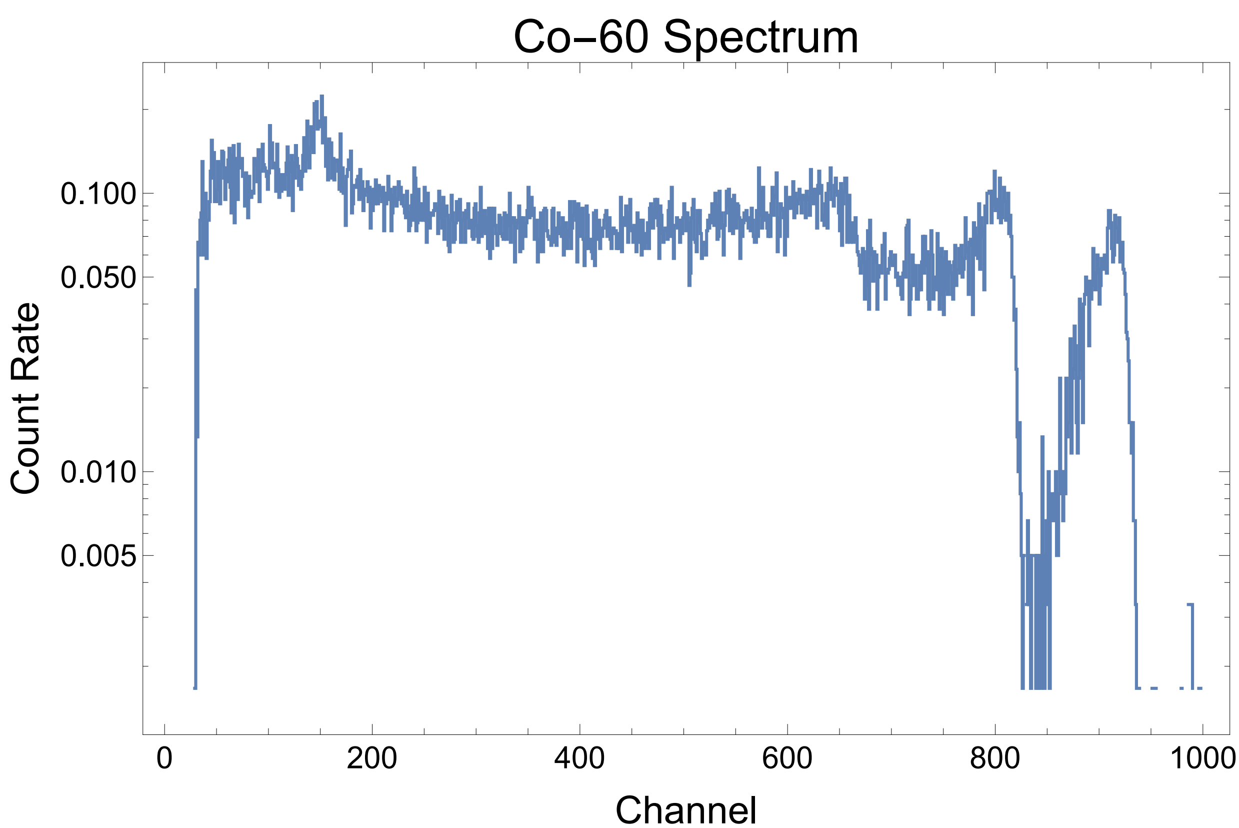
Out[156]= 600

Out[157]= {{800, 0}, {910, 0}}

Out[159]//TableForm=

Peak Channel	Energy (keV)
800	1173
910	1332

Out[162]=



In[163]:=
```
countsCo60CZT = data;
Co60CZTDeltaV = 10 / 1024;
```

Co-57

In[165]:=
```
datafile = "Co_57_300sec.Spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
time = ToExpression[
  StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[10]]][[1]]]
peaks = {{85, 0}}
energies = {137};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data / time - bgdata / bgtime;
channels = Table[x, {x, Length[data]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Channel", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Co-57 Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

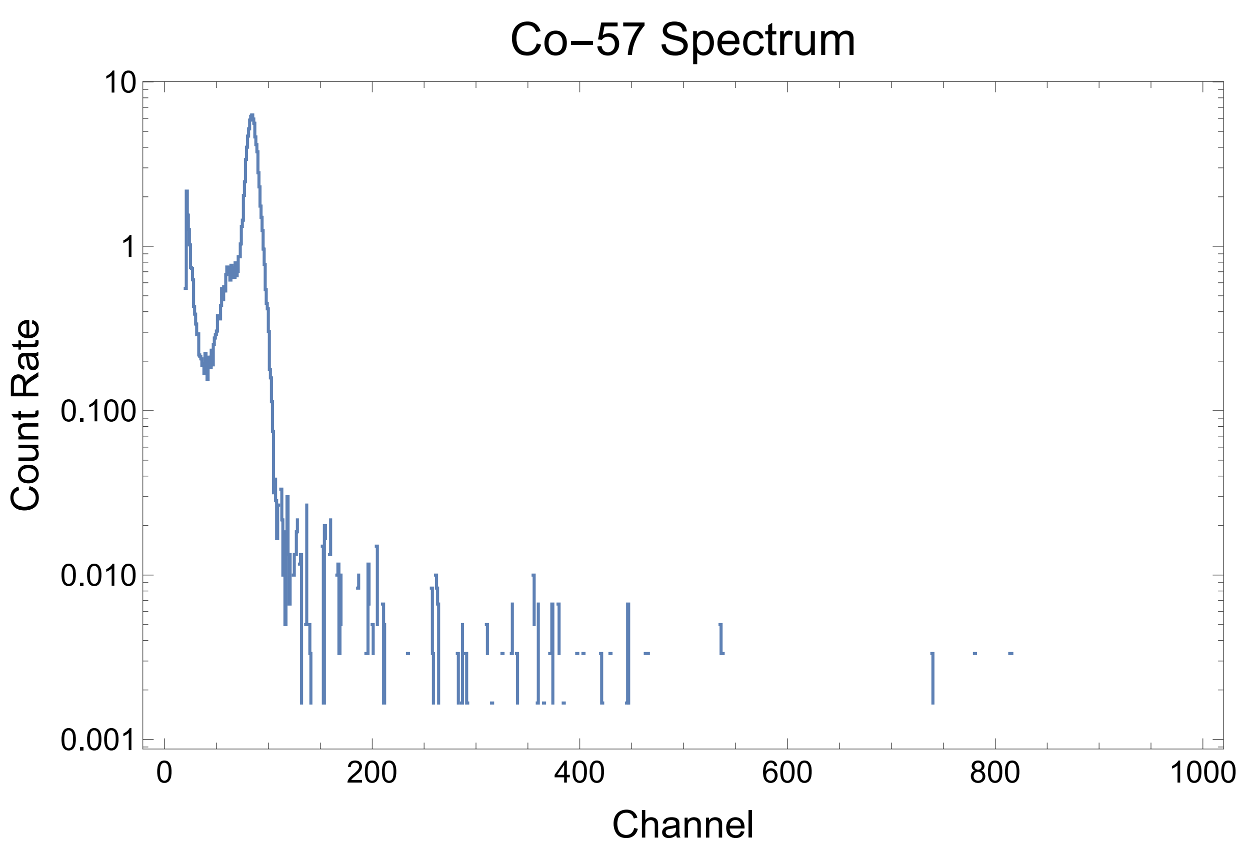
Out[167]= 300

Out[168]= {{85, 0}}

Out[170]//TableForm=

Peak Channel	Energy (keV)
85	137

Out[173]=



Cd-109

In[174]:=
```
datafile = "Cd_109_300sec.Spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -16]]];
time = ToExpression[
  StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[10]]][[1]]]
peaks = {{70, 0}}
energies = {88.04};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data / time - bgdata / bgtime;
channels = Table[x, {x, Length[data]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Channel", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Cd-109 Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

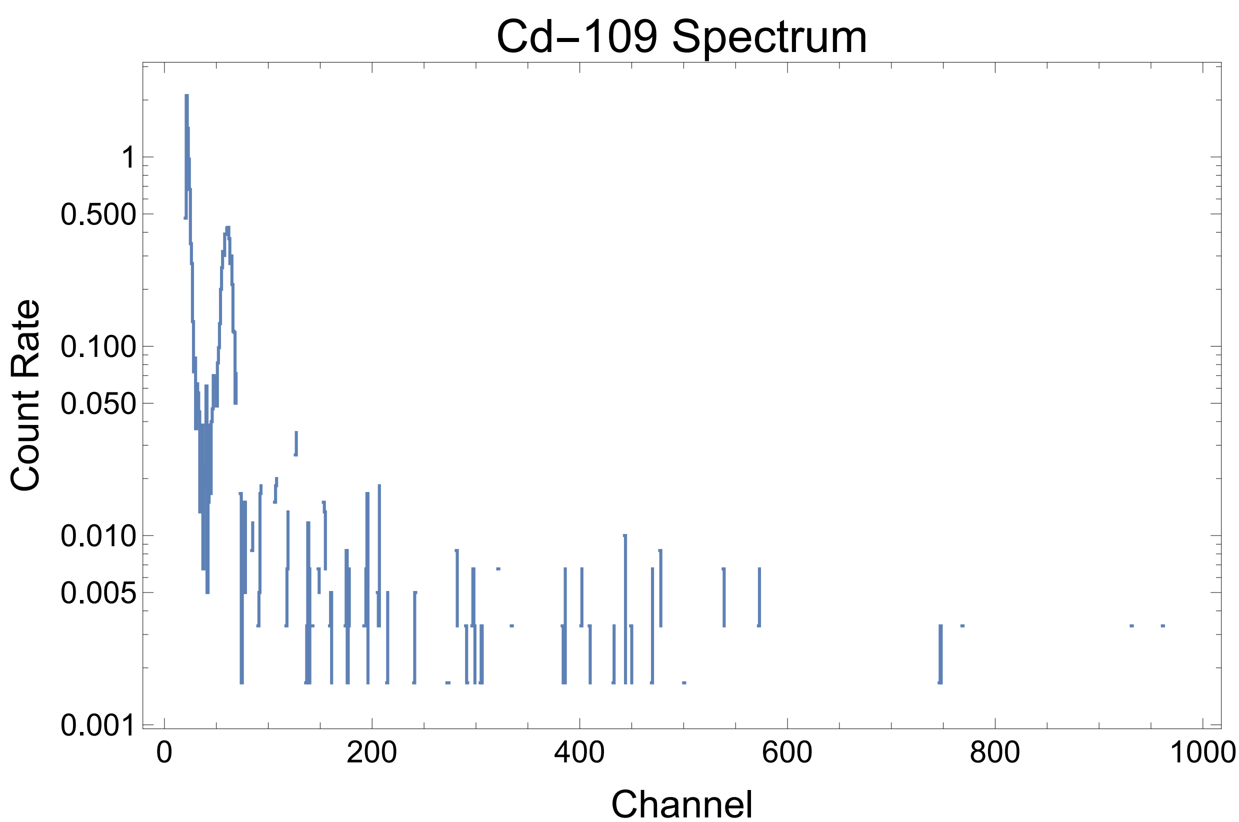
Out[176]= 300

Out[177]= {{70, 0}}

Out[179]//TableForm=

Peak Channel	Energy (keV)
70	88.04

Out[182]=



Ba-133

In[183]:=
```
datafile = "Ba_133_300sec.Spe";
data =
  ToExpression[StringSplit[Import[datafolder <> datafile], "\n"][[13 ;; -15]]];
time = ToExpression[
  StringSplit[StringSplit[Import[datafolder <> datafile], "\n"][[10]]][[1]]]
peaks = {{25, 0}, {70, 0}, {100, 0}, {200, 0}, {215, 0}, {250, 0}}
energies = {356, 80.99, 303};
TableForm[Multicolumn[Join[Sort[peaks[[ ;; , 1]]], Sort[energies]], 2] // First,
 TableHeadings → {None, {"Peak Channel", "Energy (keV)"}}]
ratedata = data / time - bgdata / bgtime;
channels = Table[x, {x, Length[data]}];
ListLogPlot[Multicolumn[Join[channels, ratedata], 2] // First,
 Frame → True, ImageSize → Full, FrameTicksStyle → Directive[16],
 FrameLabel → {Style["Channel", 20], Style["Count Rate", 20]},
 PlotLabel → Style["Ba-133 Spectrum", 24], Joined → True, InterpolationOrder → 0]
```

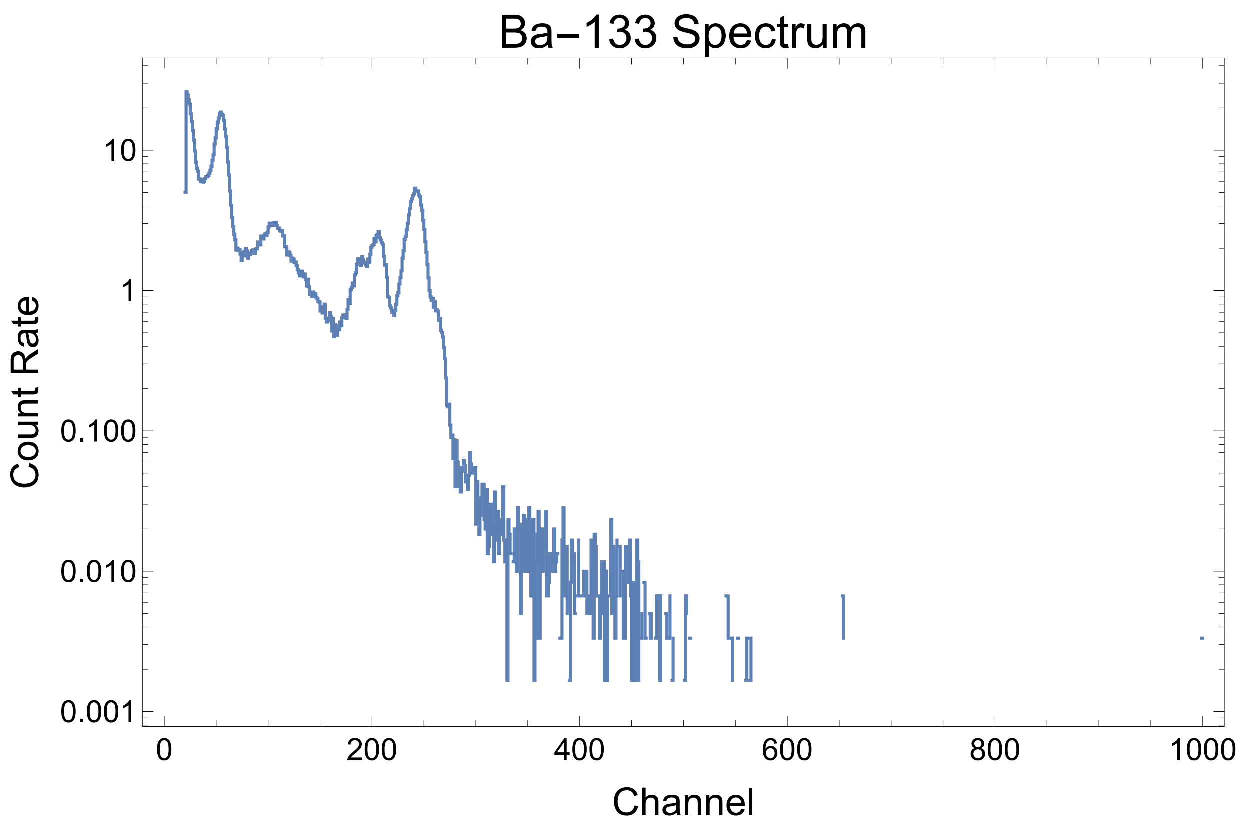
Out[185]= 300

Out[186]= {{25, 0}, {70, 0}, {100, 0}, {200, 0}, {215, 0}, {250, 0}}

Out[188]//TableForm=

Peak Channel	Energy (keV)
25	250
70	80.99
100	303
200	356
215	

Out[191]=

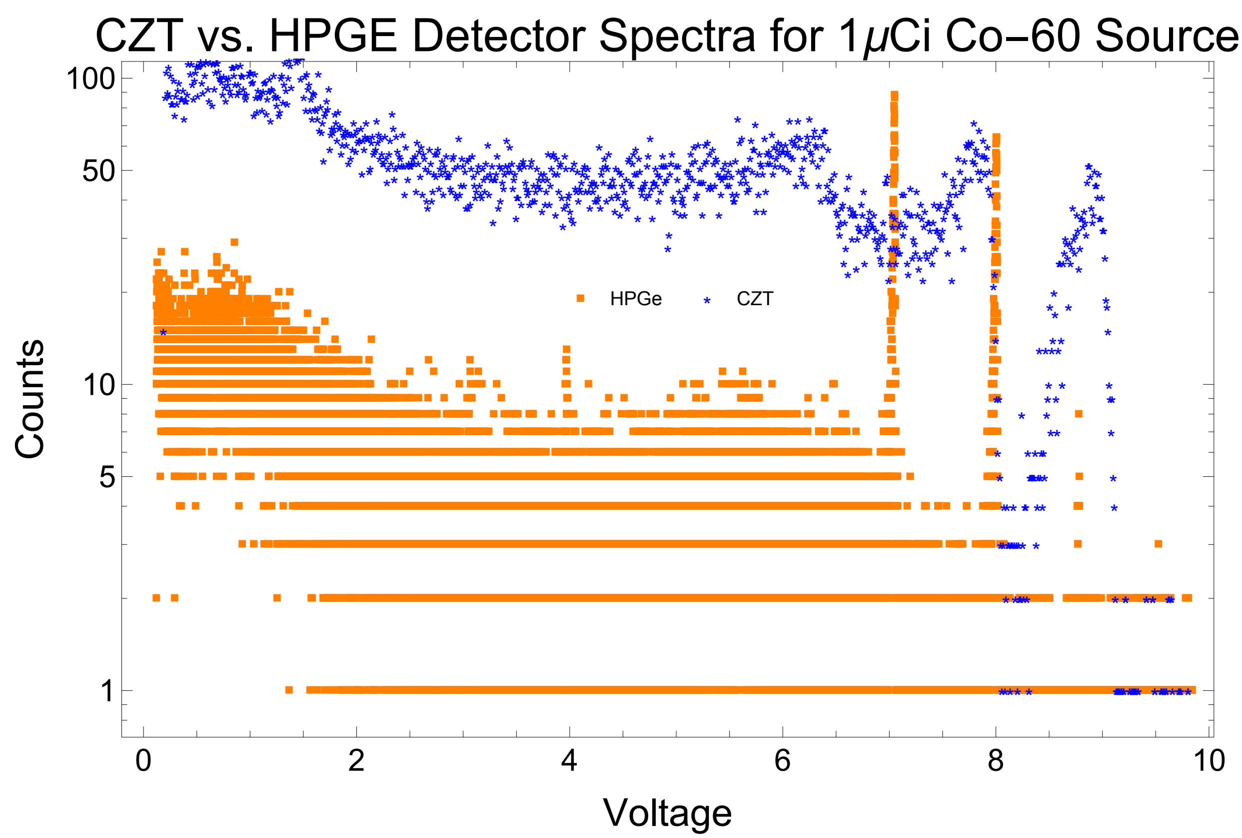


Due to the inherently lower resolution of the CZT detector, the spectra obtained resist analytical peak finding techniques. The peaks listed above were approximated visually.

2. At the end of the CZT analysis section, properly identify that the following plot is part of the HPGe and CZT comparison section. Now plot the Co-60 data for CZT and HPGe on the same plot with a legend (all other formatting requirements still necessary).

In[192]:=
```
hpgeplot = ListLogPlot[
   Multicolumn[Join[Range[0, 10, Co60HPGeDeltaV], countsCo60], 2] // First,
   PlotMarkers → Style["■", Small, Orange],
   PlotLegends → Placed[{"HPGe"}, {0.5, 0.65}], ImageSize → Full,
   PlotLabel → Style["CZT vs. HPGE Detector Spectra for 1μCi Co-60 Source", 24],
   Frame → True, FrameLabel → {Style["Voltage", 20], Style["Counts", 20]},
   FrameTicksStyle → Directive[16]];
cztplot = ListLogPlot[Multicolumn[Join[Range[0, 10, Co60CZTDeltaV], countsCo60CZT],
     2] // First, PlotLegends → Placed[{"CZT"}, {0.5, 0.65}],
   PlotMarkers → Style["*", Small, Blue]];
Show[hpgeplot, cztplot]
```

Out[194]=



3. In a text-style cell below the comparison plot, qualitatively compare the energy resolution and photopeak efficiency of the HPGe and CZT detectors using the comparison plot and the tables of data generated.

a. Which detector has a higher energy resolution?

The HPGe has significantly higher energy resolution thanks to its very small band gap.

b. Which detector has a higher photopeak efficiency?

c. Which detector is bigger, housing and all?

Thanks to the need for a liquid Nitrogen cooling system, the HPGe detector is significantly larger.

d. Choose one of the two detectors as the best detector. The reason behind the choice can vary because it includes many factors (including application as desired by the student during the comparison). Be sure to justify your reasoning.

Silicon Detector

1. Plot the collected spectra in counts vs. channel number on a single plot. In a text-style cell, comment on the trend observed with increasing bias. Further comment on the shape of the peaks and how they evolve with increasing bias. Theorize what is fundamentally going on to exhibit such a behavior.

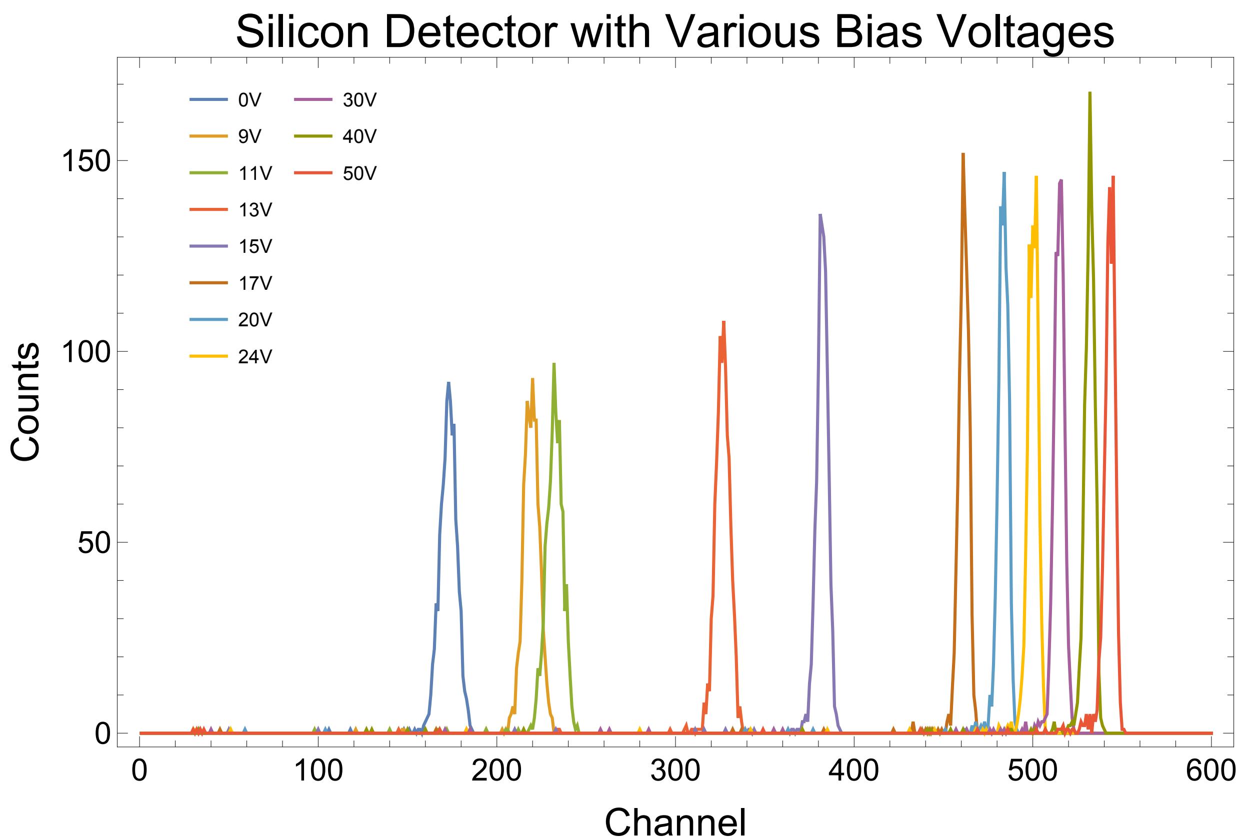
```
In[195]:= datadir = NotebookDirectory[] <> "data/silicon/"
Out[195]= /Users/jrpowers-luhn/nucnotes/ne550/Lab 8/data/silicon/
```

In[196]:=
```
filenames = {
   "Volts_0.Spe",
   "Volts_9.Spe",
"Volts_11.Spe",
"Volts_13.Spe",
"Volts_15.Spe",
"Volts_17.Spe",
"Volts_20.Spe",
"Volts_24.Spe",
"Volts_30.Spe",
"Volts_40.Spe",
"Volts_50.Spe"
  };
spec[filename_] :=
 ToExpression[StringSplit[Import[datadir <> filename], "\n"][[13 ;; -18]]]
```

In[198]:=
```
spec["Volts_0.Spe"];
```

In[199]:=
```
ListPlot[Map[spec, filenames][[ ;; , ;; 600]], ImageSize → Full,
 Joined → True, PlotLegends → Placed[{"0V", "9V", "11V", "13V",
    "15V", "17V", "20V", "24V", "30V", "40V", "50V"}, {0.15, 0.75}],
 Frame → True, FrameLabel → {Style["Channel", 20], Style["Counts", 20]},
 FrameTicksStyle → Directive[16],
 PlotLabel → Style["Silicon Detector with Various Bias Voltages", 24]]
```

Out[199]=



As the bias voltage is increased, the gap between the conduction band and the valence band decreases. This means that the same energy input will cause more excitations, and therefore more current to be collected by the detector. This

2. From the alpha spectra, calculate the peak channel number, standard deviation, and standard deviation of the mean. Report the numbers in a properly formatted table (applied bias, peak channel number, standard deviation, standard deviation of the mean, FWHM, and energy resolution).

In[200]:=
```
Remove[filename]
```

In[201]:=
```
pk[nme_] := FindPeaks[spec[nme], 100, 10^-8, 75];
```

In[202]:=
```
peakvolts = Map[pk, filenames][[ ;; , ;; , 2]][[ ;; , 1]];
```

In[203]:=
```
peakchannels = Map[pk, filenames][[ ;; , ;; , 1]][[ ;; , 1]];
```

In[204]:=
```
stddevs = Table[StandardDeviation[spec[f]], {f, filenames}] // N;
```

In[205]:=
```
biasvolts = {0, 9, 11, 13, 15, 17, 20, 24, 30, 40, 50};
```

In[206]:=
```
fwhm = Table[2 * Sqrt[2 Log[2]] s, {s, stddevs}];
```

In[207]:=
```
resolution =
  Table[2 Sqrt[2 Log[2]] / (p[[1]] / p[[2]]), {p, Multicolumn[Join[peakvolts, stddevs], 2] // First}]
```

$$\text{Table}\left[\frac{2\sqrt{2\,\text{Log}[2]}}{p[[1]]\,/\,p[[2]]},\ \{p,\ \text{Multicolumn}[\text{Join}[\text{peakvolts},\ \text{stddevs}],\ 2]\ //\ \text{First}\}\right]$$

Out[207]=
```
{0.141986, 0.142414, 0.131755, 0.133021, 0.121768,
 0.109857, 0.116477, 0.117103, 0.118844, 0.102436, 0.117126}
```

In[208]:=
```
meandev = Table[MeanDeviation[spec[filename]], {filename, filenames}] // N
```

Out[208]=
```
{0.98771, 0.96946, 0.956508, 1.00547, 1.02937,
 0.977639, 0.999244, 1.00831, 1.02545, 1.00097, 0.992368}
```

In[209]:=
```
TableForm[
 Multicolumn[Join[biasvolts, peakchannels, stddevs, meandev, fwhm, resolution], 6] //
  First, TableHeadings → {None,
   {"Bias (V)", "Peak Location", "σ", "Mean Deviation", "FWHM", "Resolution"}}]
```

Out[209]//TableForm=

Bias (V)	Peak Location	σ	Mean Deviation	FWHM	Resolution
0	173	5.54724	0.98771	13.0627	0.141986
9	220	5.62443	0.96946	13.2445	0.142414
11	232	5.42727	0.956508	12.7802	0.131755
13	327	6.10079	1.00547	14.3663	0.133021
15	381	7.03258	1.02937	16.5605	0.121768
17	461	7.09107	0.977639	16.6982	0.109857
20	484	7.2711	0.999244	17.1221	0.116477
24	502	7.26046	1.00831	17.0971	0.117103
30	516	7.3179	1.02545	17.2323	0.118844
40	532	7.3081	1.00097	17.2093	0.102436
50	543	7.11268	0.992368	16.7491	0.117126

3. From the data (voltage, peak channel number, and SDOM), find the weighted fit of the modified Hecht's relation provided in the experimental section.

a. Assume that the detector is 150 μm thick.

In[229]:=
```
d = 150 * 10^-6;
hecht[V_, mutau_, A_] := A (mutau V)/d^2 (1 - e^(-(d/V) (d/mutau)));
fitdata = Multicolumn[Join[biasvolts[[2 ;;]], peakchannels[[2 ;;]]], 2] // First
fmodel = NonlinearModelFit[fitdata, A * (mutau * V)/d^2 (1 - e^(-(d/V)*(d/mutau))), {A, mutau}, V]
```

Out[231]=
```
{{9, 220}, {11, 232}, {13, 327}, {15, 381}, {17, 461},
 {20, 484}, {24, 502}, {30, 516}, {40, 532}, {50, 543}}
```

Out[232]= FittedModel[$-2.07585\times10^{16}\left(1-e^{2.05675\times10^{-14}/V}\right)V$]

In[234]:=
```
fmodel["Properties"]
```

Out[234]=
```
{AdjustedRSquared, AIC, AICc, ANOVATable, ANOVATableDegreesOfFreedom,
 ANOVATableEntries, ANOVATableMeanSquares, ANOVATableSumsOfSquares,
 BestFit, BestFitParameters, BIC, CorrelationMatrix, CovarianceMatrix,
 CurvatureConfidenceRegion, Data, EstimatedVariance, FitCurvatureTable,
 FitCurvatureTableEntries, FitResiduals, Function, HatDiagonal,
 MaxIntrinsicCurvature, MaxParameterEffectsCurvature, MeanPredictionBands,
 MeanPredictionConfidenceIntervals, MeanPredictionConfidenceIntervalTable,
 MeanPredictionConfidenceIntervalTableEntries, MeanPredictionErrors,
 ParameterBias, ParameterConfidenceIntervals, ParameterConfidenceIntervalTable,
 ParameterConfidenceIntervalTableEntries, ParameterConfidenceRegion,
 ParameterErrors, ParameterPValues, ParameterTable, ParameterTableEntries,
 ParameterTStatistics, PredictedResponse, Properties, Response,
 RSquared, SingleDeletionVariances, SinglePredictionBands,
 SinglePredictionConfidenceIntervals, SinglePredictionConfidenceIntervalTable,
 SinglePredictionConfidenceIntervalTableEntries,
 SinglePredictionErrors, StandardizedResiduals, StudentizedResiduals}
```

In[235]:=
```
fmodel["BestFit"]
fmodel["ParameterTable"]
```

Out[235]= $-2.07585\times10^{16}\left(1-e^{2.05675\times10^{-14}/V}\right)V$

Out[236]=

	Estimate	Standard Error	t-Statistic	P-Value
A	426.951	41.8301	10.2068	7.2838×10^{-6}
mutau	-1.09396×10^{6}	1.5804×10^{6}	−0.692204	0.508399

4. Below the calculation and in a text-style cell:

a. Report the values found for the constant A and the mobility-trapping time constant ($\mu_e\ \tau_e$) with their uncertainty.

The fit converged on a value of 427±40 for A and a value of $-1.1 \pm 1.5 * 10^{6}\ m^2/V$ for $\mu_e\ \tau_e$.

b. Determine the maximum CCE obtained with the silicon detector (hint: consider the constant A) with uncertainty (hit: use equation 2.84 in the text to calculate the uncertainty in the CCE using the simple quotient of your chosen channel number from the data and the value of A).

c. Go online and find a citable reference for n-type silicon’s mobility-trapping time constant (μ_e τ_e) for electrons and compare to the values you got. Do this in a text-style cell and provide the reference as well.

The closes thing I found has some references to τ, but I can’t tell if it’s related. https://journals.aps.org/pr/pdf/10.1103/PhysRev.100.606