Imaging Low Energy Beta Decays Using an EMCCD

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Abstract

Using a CsI scintillator, a microscope and an electron multiplying charge coupled device (EMCCD camera), I was able to take data from low energy beta emitters and write analysis code to produce energy spectra. Particularly of note is a clear signal produced by a ^{14}C source. The goal of the SLIMER project is to image organic carbon in biological samples from the permafrost. Some work still needs to be done in order to image low intensity sources consistently, but we have made considerable progress and have some idea of work that needs to be done in order to improve the experiment.

DISCUSSION OF THE APPARATUS

A short description of the apparatus is that we have a CsI(Tl) scintillator on the tray of a microscope that is connected to an EMCCD. Everything is contained in a dark box that should block out all light. In addition we have designed a holder for the scintillator and a collimator in order to get reproduceable results. I'll discuss features of all aspects of the experiment and point out problems that have shown up that we think are connected to the functioning of a certain instrument.

Figure 1: The CsI(Tl) Scintillator

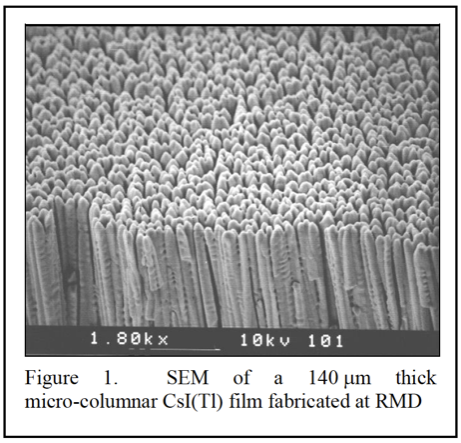


Figure 1. SEM of a 140 μm thick micro-columnar CsI(Tl) film fabricated at RMD

CsI is a very commonly used scintillation material that has a high light output of 65 photons/keV and a broad transmission spectrum. The picture shows the columnar scintillation material we use. These columns are grown using vapor deposition and the resulting columns are 3-5 μm in diameter.
Through running some simulations, we know that there should be a way to

Figure 2: The Microscope

distinguish low energy beta emitters by the energy deposited in the scintillator. And we have made progress in distinguishing them with a variety of analysis techniques. A problem that may be due to the scintillator is the reproduceability problem; it seems that every time I put a source on the scintillator I get different rates, different spectra, and sometimes it is a pretty drastic difference. The uniformity of the scintillator needs to be measured to determine if this problem is related to the nonuniformity of the scintillator.

The microscope is a Nikon Eclipse Ti Inverted Research Microscope. It was chosen for its high light transmission rate. We also have 2 Semrock filter cubes. These cubes have a high transmission rate and they will be important when we study biological samples, because we can feed bacteria flourescent dyes to determine the position of a sample and get an idea of what it looks like. There may be problems with light leaks adding to the noise. We should study in detail whether there is a significant difference between data taken with the camera shutter closed and open. Currently, we haven't looked at that, but we have some data.

Figure 3: The Camera

The camera is a Photometrics Evolve-512 EMCCD. When cooled to low temperatures EMCCD cameras can acheive a much higher efficiency than other types of CCDs. The Quantum Efficiency for certain wavelengths of light can be as high as 97%. One of the drawbacks of EMCCDs is a complicated noise signal. It is hard to understand how minor changes to the parameters in the system will effect the quality of the data. The equation of the signal-to-noise ratio is:

$$SNR = \frac{G\eta\phi_p\tau}{N_{tot}} \tag{1}$$

where G is the gain setting, η is the Quantum Efficiency, ϕ_p is the photon flux in photons per second per pixel, τ is the exposure time, and

$$N_{tot} = (N_{shot}^2 + N_{dc}^2 + N_r^2)^{1/2} \tag{2}$$

is the total noise. Going into more detail on the different types of noise:

$$N_{shot} = G \times F \times \sqrt{\eta\phi_p\tau} \tag{3}$$

is the shot noise that is due to statistical fluctuations in the number of photons emitted by an object,

$$N_{dc} = \left[2.55 \times 10^{15} \times N_{dc0} \times \tau \times d_{pix}^2 \times T^{3/2} \times e^{(\frac{E_g}{2kT})}\right]^{1/2} \quad (4)$$

is the dark current noise that is caused by thermally generated electrons in the CCD, and

$$N_r = [N_{r0}^2 + (G \times N_{ct})^2]^{1/2} \quad (5)$$

is the readout noise where N_{ct} is the charge transfer noise. I'm not going to go into every single detail because there are many. The main thing to note is that there is a strong dependence on temperature setting and gain setting. I think I have confirmed with analysis of the data I took that the temperature setting needs to be as low as possible and that gain should not be cranked up all that much.

Studies have been done on the efficiency of the system. With ^{14}C an average event is expected to generate a signal that corresponds to about 1000 photons. This should be a significant signal and I think that with the correct software and hardware settings it should be possible to consistently detect low intensity ^{14}C sources in biological samples.

ANALYSIS TOOLS

To analyze the data I wrote two sets of analysis codes. I wrote the code in python and utilized the scipy and numpy libraries, which have some powerful tools to analyze 2d arrays and pictures. One analysis method I used is to fit events as a bivariate normal distributions. The other analysis code is meant to define a cluster of coordinates for an event. I've found that the cluster analysis code is advantageous to use, because the data does not end up corresponding perfectly to a nice normal distribution and the cluster fills out the shape of each event more accurately. Now I will go into the details of what I do in each code.

For both analysis methods I start by making background cuts based on the average of each pixel throughout a background run, I gaussian smooth the data and define a threshold, then I find features that are above the threshold, and finally I apply a 2d gaussian fit or I find the coordinates of each feature individually. The threshold is found by recursively filtering out the peaks in the data and finding values for the mean and standard deviation of the data set that are close to what these values are for the background data set. To filter out background peaks I make a rough estimate of how large the peak is and apply cuts to peaks that are too small or large to be anything significant. The fit outputs: x sigma, y sigma, peak height, x coordinate, y coordinate, and background value. These values are used to calculate integrals, areas and peak heights for the raw data, the gaussian smoothed data and the fit data.

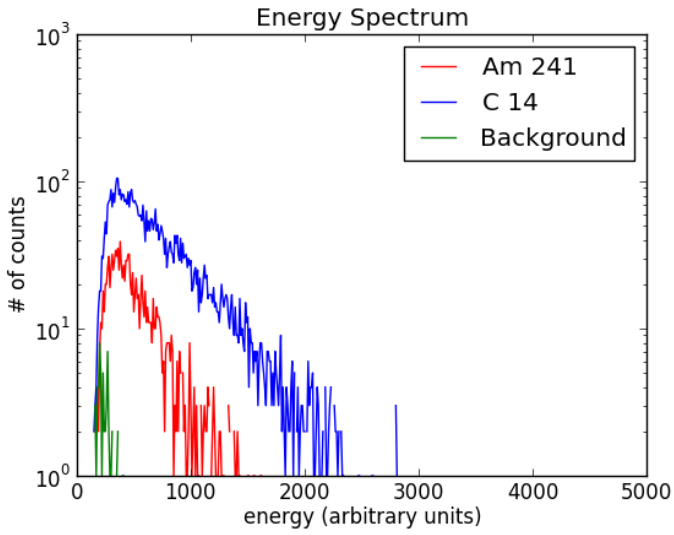
RESULTS

For the most part I have used basically the same settings ever since the first time I saw something significant with a ^{14}C source on the scintillator. I've used

200 msec exposures, 1 hour runs, a multiplication factor of 200, a conversion gain of 1/6x, a magnification of 20x, and a scintillator that is 45 μ thick. The temperature of the EMCCD has changed a little bit. I've mostly taken runs at -80°C. At some point I think that one set of runs I took was at the minimum temperature around -84°C. If I'm right this small change in temperature had a very significant effect on the signal-to-noise ratio. It not only amplified the number of events, but the energy spectrum in arbitrary units produced by my analysis code. This makes sense because my code sets a threshold and looks for anything significant above that threshold and does some integrals after some cuts from the data. If the signal-to-noise ratio is greater, then the integrals will produce larger results on average. For the following graphs I've used my cluster algorithm exclusively and I've used the integral over the gaussian smoothed data in a defined area as the value of interest. In addition, I've used the same binning for all the plots.

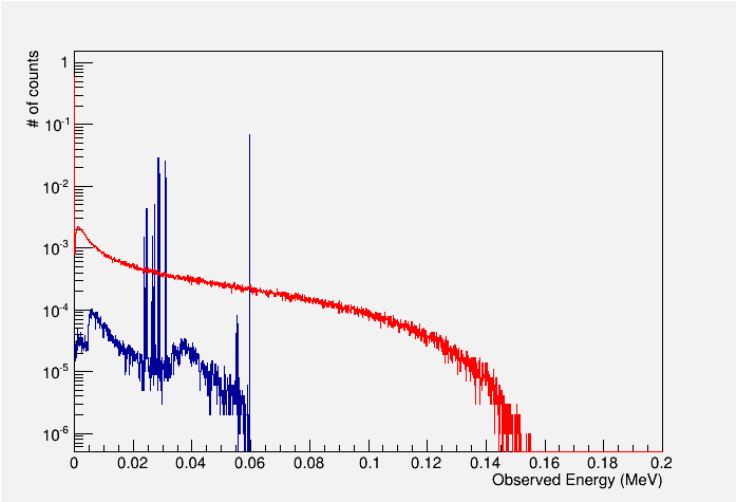
In Figure 4 we see that the analysis can distinguish between two low energy sources over a one hour run. We are looking at data from a ^{14}C β source and a ^{241}Am γ. The main peak of ^{241}Am is a 59.5 keV peak and the ^{14}C β spectrum has an endpoint of 156.48 keV and an average energy of around 49 keV. Figure 5 is the results of a simulation of how much energy should be deposited in the scintillator by the two different sources shown in Figure 4. It is apparent that what we are seeing in analyzing these low energy source runs is possibly consistent with simulation results. Although if this is correct the ^{241}Am spectrum has been considerably blurred and looks like one peak. This could be caused by anything from an optical effect, to a camera effect, to something that has been introduced by the code.

Figure 4: Cold ^{14}C and ^{241}Am Runs on 7/10/2013



After I acheived these results I ran into problems with reproducing the high count rate. With the last iteration of my code I was seeing 16,276 events with

Figure 5: ^{14}C and ^{241}Am Simulated Runs



the ^{14}C source on the scintillator and 2,139 events without it. That's 14,137 events above the background per hour. If this was the low intensity source that is 20 times weaker at 45 nCi, instead of 1 μCi, then we could get about 700 events an hour with the low intensity source and over 100 events per hour from a biological source. If that were the case, then it would be possible to do a 12 hour run on a biological source and get a significant result. Unfortunately, after taking this data I was not able to reproduce the same results again, but I have investigated the issue and may have found some insights.

With following runs I would see event rates similar to what I got in Figure 6 and Figure 7. In Figure 6 there are 1,740 ^{14}C events and 438 background events, which is 1302 source events and in Figure 7 there 2,636 events and 455 background events, which is 2,181 source events above the background. These results I thought were taken using the exact same settings as before and I was puzzled that there was such a huge decrease in event rate. I certainly didn't expect my method of taking data to produce the exact same result every time, but an order of magnitude difference is certainly a cause for concern.

One possible explanation for what happened is that I accidently changed one of the parameters in the system and I was suspicious that the high count run was at the minimum temperature of the EMCCD instead of my usual setting of -80°C. If you look at Equation 4 for the dark current noise you see that there is a strong dependence on temperature. I thought this could explain the difference and that if I ran with lower temperatures again, I would be able to see those high count rates again. This kind of happened, but more studies need to be done to confirm this. Unfortunately, the lowest temperature is not stable, which is a problem for reproduceability, but if you can get higher rates than it is worth having that added instability to produce better results. Figure 8 shows a run with the EMCCD at about -84°C. This was a three hour run, so you would expect a lot better statistics and a better looking graph. We got 13,233

Figure 6: Warm ^{14}C and ^{241}Am Runs on 8/01/2013

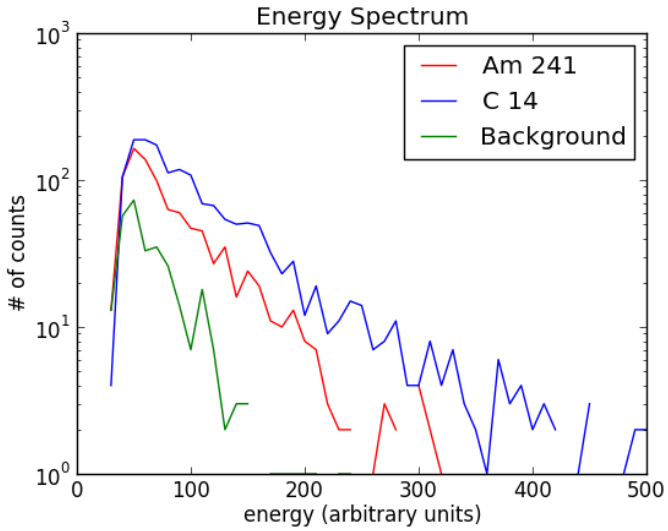
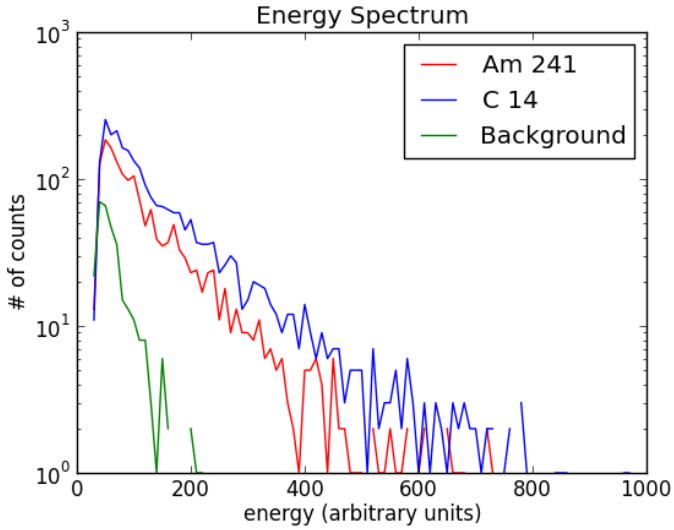


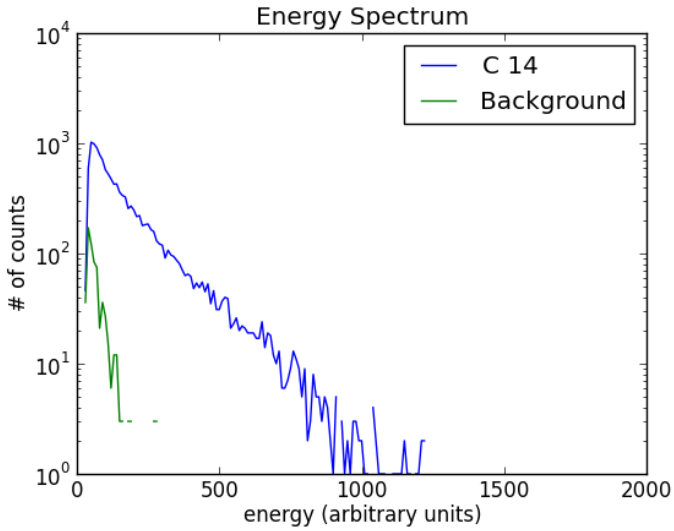
Figure 7: Warm ^{14}C and ^{241}Am Runs on 8/07/2013



events with the source and 333 events in a one hour background run, which I rescaled by a factor of 3 in the plot. So, over three hours we are getting 4,078 events per hour, which is a 2-4 times increase over what I was getting at lower temperatures. This shows that a small change in temperature can significantly effect the count rate. It still does not achieve rates that are as significant as we found before and it does not explain the high background rate that we saw before, but maybe I found a reason for the success of that one run.

Another question that I asked is that if this result was in the bounds of

Figure 8: Cold ^{14}C Run on 8/13/2013

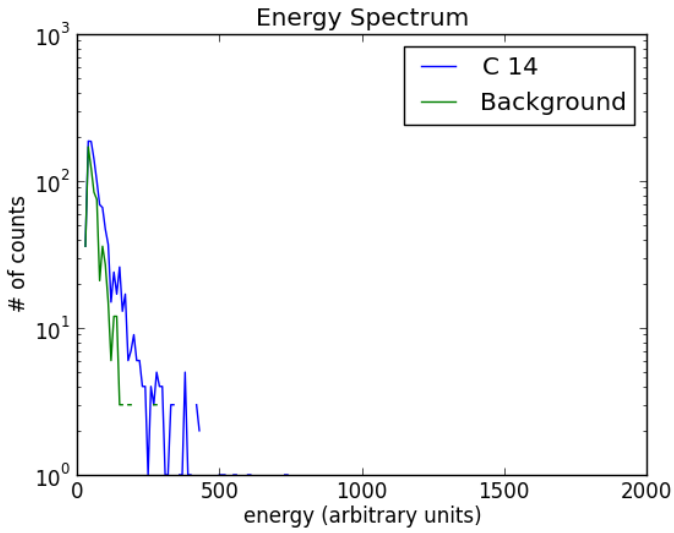


reason of what I could expect. With a very simple estimation I was able to determine that the higher event rates are possible. With some help I found an estimation for what the count rate could be from a circular hot spot on the source to the area the microscope is zoomed in on. The number of beta events to hit the picture area per second would approximately be $0.5 \times Activity \times \frac{area1}{area2}$. The area2 is the hot spot on the sources we use, which is expected to be 3mm in diameter, area2 is the picture size, which is measured to be 0.8 μm/pixel, and the Activity is 1 μCi = 37000 decays per 200 msec. This comes out to be 87.8 events per 200 msec exposure. This is a crude estimation, but it has been used before and given results that aren't too far off. So, it seems like 14,137 actual events for an hour run that outputs about 10,000 pictures is not only possible, but improvements may be made to detect more events.

If you look back at the pictures you see a lot of inconsistencies in energy scale and count rates. To try and get more consistent data we designed a simple holder that we could use to position the source consistently. Unfortunately the count rates are severely impacted by putting the source in a collimator. We think that this is mostly because the source hot spot is larger than the hole in either collimator. Figure 9 uses a collimator with a 1mm hole and it is from the same day as Figure 8, so you would expect the count rate to be comparable. We got 1389 events to the same 1000 event background. So, it turns out to be about 130 events per hour. If the source activity was centered, circular and uniform you would expect the most events the collimator could cut out would be $(1.0 - \frac{\pi(0.5mm)^2}{\pi(1.5mm)^2}) \times 100\%$, which turns out to be about 89%. If you removed the collimator with the same assumptions you would expect to get about 1180 events per hour. The fact that this expectation is so much lower than the actual counts I got without the collimator and with the source not perfectly centered suggests that we cannot assume that the source is uniform, or circular, or centered. In addition, it could be that the scintillation material does not scintillate

uniformly across its surface and that any change in the position of where you are looking at the scintillator will change the event rates and possibly the resulting spectrum as well. Some of these problems shouldn't be as important with biological samples because we'll be able to use flourescence to pinpoint where to take data, but it is a stumbling block for getting consistent data with the sources we have available. It also means that any estimates we make of what count rate we can expect from a biological source will not end up being accurate until we have a better understanding of what is happening.

Figure 9: Cold ^{14}C Run with Collimator on 8/13/2013



With the understanding that I could get better results even with a slightly lower temperature, the last thing I tried was take a cold, low intensity 45 nCi ^{14}C source run for 4 hours in order to get some kind of low intensity result. Figure 10 shows a similar plot to previous plots only for this low intensity source run. We got 2,225 events compared to 1,536 background events. That is 689 events over 4 hours, which is 172 events per hour compared to 384 background events per hour. This isn't a great event rate, but it was expected to be about this low. For a cold run I might have expect better results, but it is not terrible. Because the statistics are not as good I added in Figure 11, which is a background division. It does seem like there is a part where the background is dominant and then the source takes over. You get a fairly distinct upward slope that tells you the source data can be distinguished from the background data and its high energy tail is sloped less steeply than the background.

Figure 10: Cold ^{14}C Run on 8/15/2013

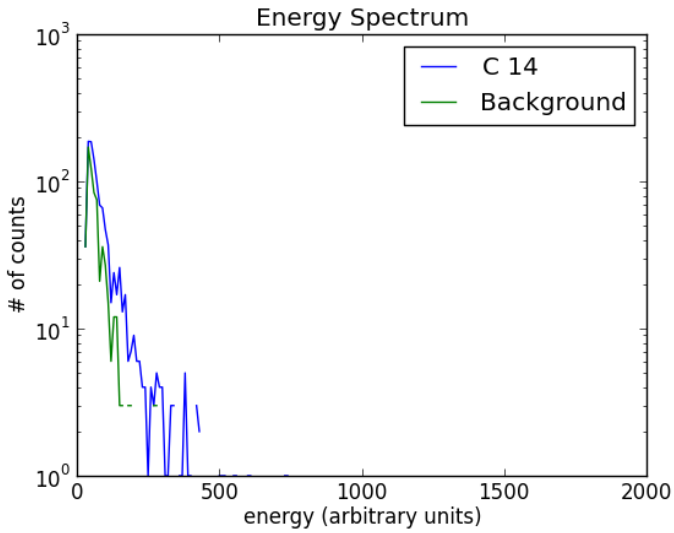
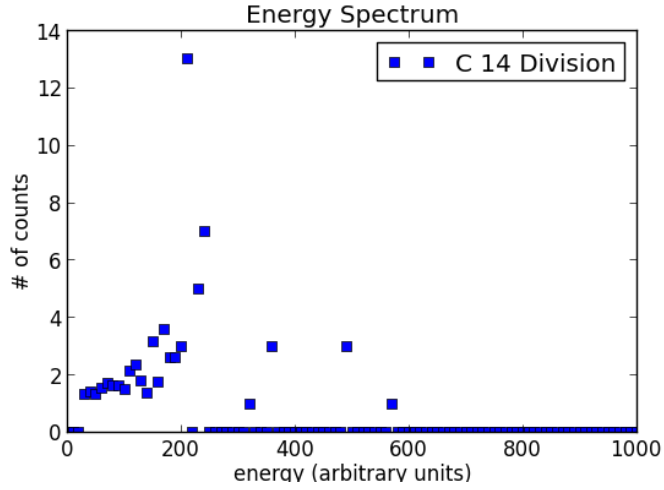


Figure 11: Cold ^{14}C Run Background Devision on 8/15/2013



CONCLUSION

These results suggest that looking at biological samples is possible and with the more developed methods for looking at biological samples we might expect better and more consistent results than from other sources. Moving forward, more consistent methods should be used to get information about the problems I've discussed. Knowing more about these problems will allow us to improve our ability to use our hardware effectively. If we manage to make progress on improving our data taking methods, then it seems that this set up will likely be able to image ^{14}C in biological samples. We definitely have results even from a low intensity source, so if we make progress in amplifying the number of events our camera can detect we should be able to get a consistent signal from any source we are interested in.

Informal Bibliography

1. Noise performance comparison of ICCD with CCD and EMCCD cameras, David Dussault; Paul Hoess
2. SLIMER-9-06-11.pdf, Mary Kidd (expected photon count for ^{14}C and some info about the scintillator)
3. Manuals for the microscope and camera