

Gamma and X-Ray Spectroscopy

A PAN Experimental Series

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July 7, 2016

Introduction

Gamma rays and **x-rays** are types of electromagnetic radiation, which comes in the form of particles of light known as **photons**. Along with ultraviolet, visible light, and infrared light, as well as microwave and radio waves, these high-energy, short-wavelength photons comprise the spectrum of light. (Fig 1). As you may know, the light that you can see with your eyes is only a very small portion of the entire spectrum of radiation, and gamma- and x-rays are the most energetic forms of the photons that also make up the light that enters your eyes.

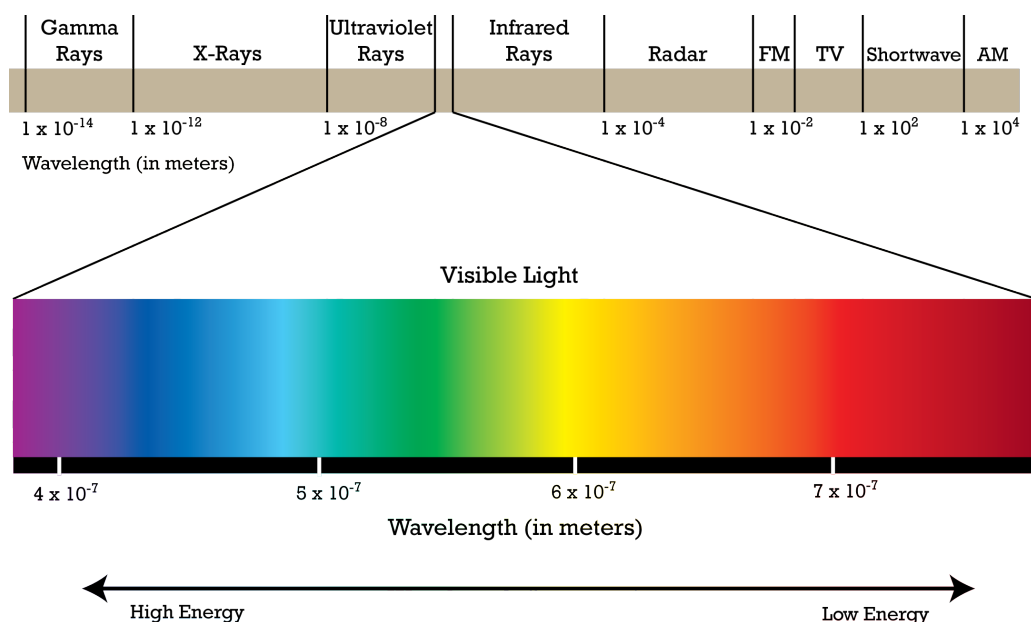


Figure 1: The spectrum of light, showing different types of electromagnetic radiation from high-energy gamma-rays to low-energy AM radio waves. In each of these cases, what enters the detector is a particle called a photon. The wavelength of the radiation is given in meters.

Both gamma-rays and x-rays are produced primarily in **atomic** and **nuclear processes**. X-rays are emitted primarily as a result of atomic de-excitation, when an electron moves from a higher-energy state to a lower-energy state. Gamma-rays are the result of a similar process, except instead of an electron moving from a higher-energy atomic state to a lower-energy state, the **nucleus itself** moves from a higher nuclear energy state to a lower state.

Observation and identification of gamma-rays is very important to nuclear scientists, since

many important nuclear processes result in the emission of one or more gamma-rays of specific energies. Astronomers use specific types of telescopes to search for high-energy photons that they know correspond to specific physical processes, and observing those photons helps scientist determine that these processes are happening right now throughout the Universe.

Experimenters can then use **detectors** similar to the equipment you'll use today to help experimentally constrain how those processes occur. Using particle accelerators like the coupled cyclotrons here at the NSCL, experimenters can create exotic and short-lived nuclei in excited energy states, move them to photon detectors, and observe them undergoing the same nuclear processes, often **decays**, that happen in space and produce the same high-energy photons. For example, in the cases of cesium-137 and europium-152, two well-known radioactive nuclei, the unstable nucleus undergoes **beta decay**, leaving the daughter nucleus in an excited state from which it can **gamma decay**, producing a photon which a detector can observe.

Often, the goal of the experimenters is to help produce a **decay scheme**, a graphic that depicts both how likely the decay is to populate each energy state in the nucleus, as well as how the various energy levels in the nucleus decay from one to another in the attempt to reach the lowest-energy state. Some examples of decay schemes can be found in Figure 2. Graphics like these are an integral part of nuclear research, as they provide extremely quick references for researchers trying to identify observed gamma-rays in an experiment.

In the process of building these decay schemes, experimenters typically record many decays using gamma-ray detectors and build up a characteristic gamma-ray energy **spectrum**. For the purposes of this type of science, the word "spectrum" refers to a histogram that records the number of times photons of different energies are observed in the detector. For our experiment, we will refer to a single detection of a photon as an "event." For example, in Figure 3, there is a large number of events peaked around 661.7 keV, the same energy shown in the cesium-137 decay scheme in Figure 2. In fact, analysis of spectra like the one in Figure 3 is often necessary for the production of accurate decay schemes.

In today's experiment, we'll learn about the equipment scientists use to perform gamma-ray spectroscopy, and look at a few ways to learn about nuclei using radiation detection equipment. **Even though the radioactive materials we will be using are low-activity and very safe, it is important to practice good radiation safety technique. Only your facilitators will be handling the radioactive sources, and they will instruct you on the best way to practice safety while working with radiation.**

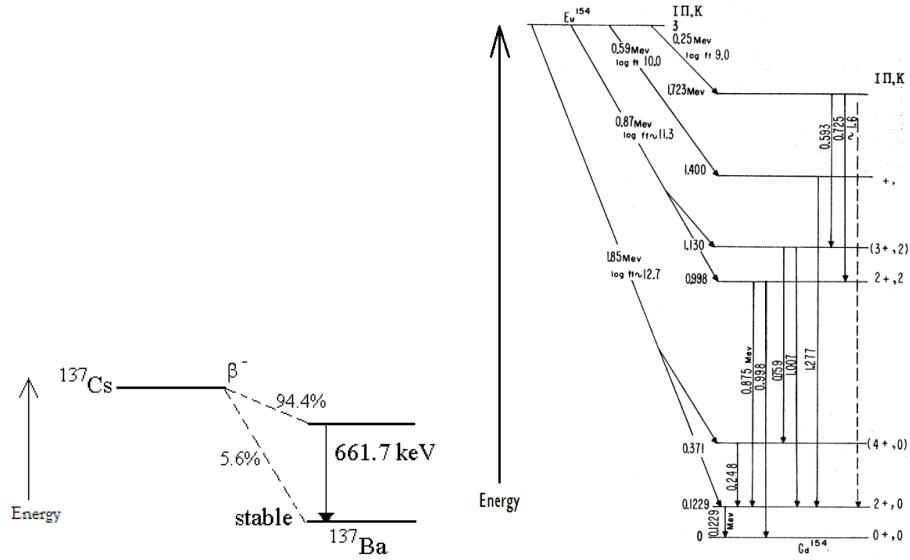


Figure 2: Beta-decay schemes for cesium-137 and europium-154. In both cases gamma rays are produced, but note that only one specific gamma ray is produced for the cesium while many energy levels are populated in the complex europium beta-decay, yielding gamma rays of various energies.

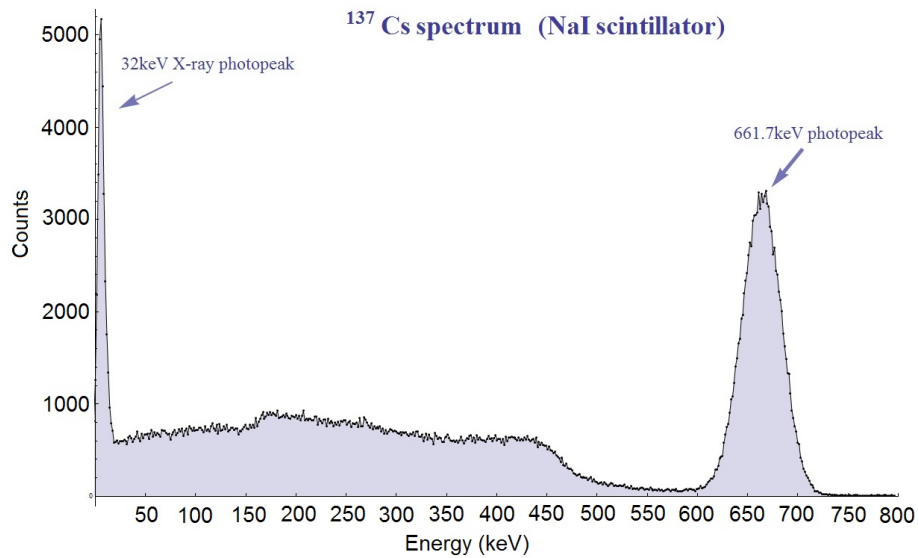


Figure 3: Gamma spectrum for the decay of cesium-137. Note the large peak corresponding to the gamma-decay from the excited state in Figure 2 to the ground state of ^{137}Ba .

Overview and Procedure

You are part of a team of elite researchers who have made a number of exciting and important discoveries. Public support for basic research is at an all-time high, and the government lab where you work has given you an important task: **you and your research associates will be attempting to use radiation detection equipment to develop and produce a decay scheme in an attempt to identify an unknown nucleus that is known to produce gamma rays as a result of beta decay. Similar to what would be required of a research publication, you will need to be able to both qualitatively and quantitatively describe your data, with estimations of the uncertainty in your measurements, and justify your conclusions.** In order to do this successfully, you will need not only to take into account the characteristics of your detector, but other complicating factors that can frustrate your attempts at science (of course, if we told you what these factors were, there wouldn't be anything fun for you to discover!).

Before you commence this investigation, you and your group will have time to explore the equipment you will be using, as well as the other tools you will have at your disposal: radioactive sources, data sheets and online data analysis tools, energy spectrum producing software, and previously-produced energy spectra.

Your group will then draft up a research plan detailing what steps you want to take to investigate the nucleus and build your decay scheme. The facilitators will be your sounding board and help you determine the best way for your group to proceed, but remember that whatever procedure you come up with should be agreed upon by your group members. Once you have completed your investigation, you and your group will work together to produce a decay scheme based on your findings, which you will then share with the other groups as well as with the facilitators.

Part One: Exploration

During the next forty minutes or so (your facilitators will let you know exactly how much time you have), you and your group are free to explore the experimental stations. The setups and equipment you use now will be the same equipment you will use during your official investigation, so it's important to try and understand how it works and how it can be used. Some brief explanations of what is available:

Sources

In exploring the experimental stations, you will be allowed to use two sources that have been studied very well: cesium-137 (detailed in Figure 2) and cobalt-60. Information about these sources is located online at the **NuDat 2.6** database and the **LBNL Radiation Search**, both of which the facilitators can help you use (the web addresses are listed in Appendix A). In addition to helping you understand how your detector works by using the oscilloscope, the cesium and cobalt sources can

help you understand how the detector interacts with the spectrum software. **Remember that only a facilitator should handle the sources.** There are also other less stringently-controlled radioactive sources that you can use while trying to understand your detector, as well as multiple types of radiation shielding that are available.

Oscilloscope

Your detector can be connected either to a computer through a multi-channel analyzer, or to an oscilloscope. The facilitators can help you connect a scope to your detector such that you can observe the electric signal that the detector sends out. This is useful for scientists in understanding whether the detector is working properly, what sorts of signals you might expect to see, and the relative strength and frequency of events in the detector. You may benefit from exploring these facets of the detector-source relationship: for example, what happens on the scope when you move the source closer to or farther away from the detector? What happens when you remove it entirely? There are more facets of this relationship than are listed here so be diligent about experimentation!

Spectrum Software

A few detectors are connected to computers with UCS20 software. The facilitator will help you learn how to use this software to accumulate gamma-ray spectra. You are free to experiment with the detector, sources, and software to produce whatever kind of spectrum you think might be useful in your investigation. As with the oscilloscope, it is important to investigate the relationship between the source, the detector, and what you see in the spectrum. Be thinking about ways you can make this system work for your investigation! **Appendix B** discusses a few details of the software so that you don't have to waste time just figuring out how to use it.

Additional Spectra

In addition to the spectra you can generate yourselves, two pre-generated spectra are available for you to study and explore. First, a printed out europium-152 spectrum is available, along with its data sheet and decay information. Some interesting things to explore might be the relationship between the listed intensities of the gamma-rays and what you observe in the spectrum, and how the gamma rays of various energies are assigned in the decay scheme. Second, a spare detector has been left on, collecting data in the room with no source in front of it, producing a so-called **room background spectrum**. You may wish to consider what this spectrum shows and what it means, as well as how it might affect your investigations.

Each group has access to the same setup in terms of detector and spectrum software, but unfortunately the government only has so much money to give to researchers, so there is only one room background spectrum. Please be mindful of your fellow scientists. As always, the facilitators can help you if you have any questions.

Part Two: Proposals

Your group will have some time (the facilitators will tell you exactly how much) to discuss as a group what you learned during the exploration phase, and to write out a plan for your investigation of the unknown nucleus. When your group is ready, you may present your group's proposal to one of the facilitators, who will let you know if any changes need to be made. Remember that in real science, proposals need to be coherent, well-argued, and goal-oriented. **Your scientific goal is to produce a decay scheme for the unknown nucleus and potentially identify it, so your proposal should reflect the pursuit of that goal.**

Once your proposal has been accepted by the facilitators, you will have some time to finalize your procedure, and then you may move on to the investigation phase! If your investigation includes use of the background spectrum, the facilitators will help schedule interested groups. **As in real science, new constraints may crop up at any time, so be thoughtful about the repeatability of the procedure you draft for your investigation!**

Part Three: Investigation and Presenting

Your group will have time to put your procedure into action. Remember that your goal is to develop a decay scheme for the unknown nucleus and potentially identify it, and your time should be spent in pursuit of that goal! The facilitators can help you obtain unknown nucleus sources (remember that only the facilitators should handle the source), and assist you in setting up the equipment, but remember that you and your group are the principal investigators here. Once you think you have enough data, try to draw up and quantify your decay scheme like the examples in this handout and the data sheets for the cesium and europium sources (hand-drawn on paper is fine). Information on quantifying uncertainty can be found in Appendix A.

After your group is satisfied with your results, spend some time discussing how you will present your findings to the other groups. You may wish to show your decay scheme, or detail your experimental procedure, among many other things. The facilitators will keep track of time so that you know how much time you have for analysis before presenting.

Appendices

Appendix A: Useful Information

Web Resources

NuDat 2.6 Database: This database has a chart of the nuclides containing information about almost all known nuclei, including energy levels, decay schemes, masses, etc. Not all of the information here is pertinent to this investigation, but it is a very useful tool for nuclear scientists. Its web address is: <http://www.nndc.bnl.gov/nudat2/chartNuc.jsp>

LBNL Radiation Search: This database contains information on different radiation, compiling it according to energy and source. If you are trying to determine if an unknown gamma-ray has been studied or identified before, this is a useful tool. Its web address is: <http://ie.lbl.gov/toi/radSearch.asp>

Conversions

Just in case you are dying to know, 1 keV is equal to 1.602177×10^{-16} joules, or 3.829×10^{-23} kCal. The energy in one donut is approximately 6×10^{24} eV. Something to bring up the next time you're at a party.

Error Analysis

In the context of research publications, it is important to quantify both the results of your study and how well you have determined those results. For gamma-ray spectrum analysis like we are doing today, the main quantities to report are the **energies** and **intensities** of gamma-rays. Energies are of course useful in determining where to place energy levels of the nucleus, and intensities help scientists infer how likely the parent nucleus is to decay to a particular state. In terms of a gamma-ray energy peak, the energy is often given by the **centroid** of the peak (where the center of the peak is), and the intensity is often given by the **integral** of the peak (how many counts are in the peak).

Uncertainty in both of these cases is fairly easy to determine. For a peak that follows the standard Gaussian statistical distribution like the peak in Figure 3, events will be centered around the centroid with a characteristic **full width at half maximum**. Since the FWHM quantifies the “spread” in the peak, the easiest way to quantify uncertainty in the centroid is as follows:

$$\sigma_{\text{centroid}} = \frac{\text{FWHM}}{2.355} \quad (1)$$

where 2.355 is mathematically determined from the Gaussian distribution shape. Note that this error is not what researchers with peak-fitting software would use, but it's appropriate for our purposes today.

For the integral of the peak, it is tempting to think that there is no error since the software simply reports a number. What the error actually quantifies in this case is how likely you would be to get the same integral result a second or third or n th time given the same measurement. Just like with the centroid, uncertainty in the integral is given as a measure of how confident you are in your results.

Nuclear decay is a statistically random process: as you already learned, a half-life is a measure of how quickly a give nucleus decays, but any given decay can happen at any time. Since the decays that contribute to gamma-ray energy peaks are random, it is appropriate to use treat each individual decay as a Poisson event, and use the associated error:

$$\sigma_{\text{Integral}} = \sqrt{\text{Integral}} \quad (2)$$

This is definitely not a statistics exercise, and physicists don't really understand statistics anyway, so if you're interested in where these errors come from or why it's appropriate to use the distributions and approximations we do here, I encourage you to check out Louis Lyons' excellent book *Statistics For Nuclear and Particle Physicists* because we will not be covering that today! If you are feeling particularly gutsy, consider the sources of your error, and whether your error is **statistical** in nature (resulting from the statistical nature of the sampling of your data) or **systematic** in nature (resulting from some aspect of your experimental setup that intrinsically introduces error into your analysis).

Appendix B: UCS20 Software

UCS is very basic spectrum-production software, but its interface isn't the most intuitive. The facilitators can help you find the various options and switches to use, but here is a list of the things you will be most likely to care about.

To start and stop taking a gamma-ray spectrum: Click the green “GO” button or the red “STOP” button near the top of the UCS window. You can also erase the accumulated events in the spectrum by clicking the button with the picture of the eraser.

To set the coarse and fine gain for the spectrum: There is a button adjacent to the “GO” and “STOP” buttons with a picture of a lightning bolt/arrow and a triangle (don't ask me). This button takes you to a window with settings for the high voltage (which you should not change), coarse and fine gain adjustments, and upper and lower threshold settings (which you should not need to change). It is probably worth exploring how changing the gain affects your spectrum.

To set a “region of interest”: In the “Settings” menu, there is an option to “set ROI” in the “ROI” submenu. Click and drag from the leftmost edge of your desired ROI to the rightmost edge. The region will be highlighted and pertinent information will be displayed below the spectrum.

To set an energy scale calibration: In the “Settings” menu, there is an option to set a 2 or 3-point calibration (you will not need the “autocalibrate” function) in the “Calibration” submenu. The 2-point calibration takes two known channels with known energies and stretches the rest of the energy axis labels to fit those two energies. You should not need to perform a 3-point calibration, but the process is similar! It may be worth considering what the effects of different calibrations are on your final result.