Lab manual
KF7: β-spectrum and Fermi-Kurie plot

PLEASE READ THIS DOCUMENT BEFORE COMING TO THE LAB!

February 6, 2017

Abstract

The purpose of this laboratory exercise is to determine the energy released in the process (the *Q-value*) for a β-transition by studying the decay of the phosphorus isotope $^{32}P \rightarrow ^{32}S + e^- + \bar{\nu}$, and to verify Fermis Theory of the weak decay. The measurements are done by a plastic scintillation detector in combination with a multi channel analyzer, and the result is compared with the theoretically calculated value.

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Contents

1 Learning outcome

In accordance with the syllabus of FYSC12: Nuclear Physics and Reactors, 7.5 credits, the goal of the laboration exercise is that the student – after completed the lab – shall:

- be familiar with the basic properties of beta-decay;
- know the main principles of how a plastic scintillator detector works;
- be able to discuss the proper setup and procedures of the experiment;
- with the help of the supervisor handle radioactive samples and use a plastic scintillator (including calibration) to measure the decay particle energy;
- evaluate experimental results.

2 Information

2.1 General

- Supervisor: Hanno Perrey, office: B202
- Email: hanno.perrey@nuclear.lu.se, please contact me for any questions regarding the lab.
- Bring: your laptop computer (with working analysis setup, see below) and a USB key.
- You have to have signed the risk assessment informing you about the safety rules in the lab before attending (will be done during the intro lecture).

2.2 Prepare BEFORE the lab

- Read Krane chap. 7.3, 7.6 (3 pages), 9.1, 9.2 and 9.3.; you should be able to say something to each of the warm-up questions in section 6.
- Read the lab manual.
- Setup your computer to run the analysis code (see section 7.1.1) and test it by following the first step.

2.3 Schedule

Morning (whole group):

- Warm-up discussion about beta decay and introduction to the experimental setup.
- Collecting and analysing data to determine the Q value of the β decay of ^{32}P.

Lunch break
Early afternoon (partner exercises/small groups):

- Open experiment session. Lots of unanswered questions from the morning: how reliable are the results, how can they be improved and what actually happens under the hood of our data acquisition system? Pick a topic to focus on and document your findings.

Later in the afternoon (whole group):

- Concluding discussion. Present your findings and ask any remaining questions you might have!

Important: For this laboratory exercise, you *do not* have to hand in any written report. Therefore, your *active* participation in the laboratory experiment is the only and key prerequisite for a passing grade: by generally asking questions, raising ideas for investigations, and by discussing the experiment and its result within the group. And of course, by following your own initiative in the afternoon when investigating a subject of your choice (see section 8) and by presenting your findings to the group during the final discussion (see section 9).

Please, do not forget to leave your feedback with the supervisor – it is greatly appreciate in the continued development of this exercise!

3 Introduction to laboratory exercise

The purpose of this laboratory exercise is to measure the energy released in the process (the *Q-value*) for a β-transition by studying the weak decay of the isotope phosphorus-32 to sulfur ($^{32}P \rightarrow ^{32} S + e^- + \bar{\nu}$) and to compare the resulting value to the theoretical expectation.

For measuring the energy of the electrons from the decay, we use a plastic scintillation detector in combination with a Multi Channel Analyzer (MCA). Two additional radioactive sources are available for the energy calibration of the detector.

Since the end point energy of the spectrum is experimentally difficult to determine from the spectrum alone, the data will be analyzed by constructing the Fermi-Kurie plot. From this, the Q-value can be easily extracted.

Finally, we will discuss whether or not the result constitutes a successful test of Fermi's Theory of weak decay.

4 Brief reminder of the underlying theory

4.1 β-decay

There are three different kinds of β decay:

β^- in this process, a neutron is converted to a proton with the emission of an electron and anti-neutrino, $n \rightarrow p + e^- + \bar{\nu}_e$. This decay occurs mainly for neutron rich nuclei; it can also happen for free neutrons.

β^+ in this process, a proton is converted to a neutron with the emission of a positron and a neutrino, $p \rightarrow n + e^+ + \nu_e$. This decay occurs mainly for proton rich nuclei, and the proton must be bound to a nucleus.

E.C. (Electron Capture) if the energy of the excited nucleus is not high enough for a $\beta^\pm$ decay, an electron near the nucleus can be captured by a proton, leaving the atom in an excited state, where the hole is filled by an outer electron, giving characteristic X-rays (the energy of the X-ray is the binding energy of the captured electron).

4.1.1 Q-value

The released energy in a nuclear reaction is called the Q-value. It can be expressed as the difference in the nuclear binding energy before and after the decay:

$$Q_{\beta^-} = [m_N(X) - m_N(X') - m_e - m_\nu] \cdot c^2 \tag{1}$$

where X is the mother nucleus, X' is the daughter, and m_N denote the *nuclear* masses.

4.2 Fermi's Theory of beta decay

In this exercise we want to determine the Q-value of phosphorus-32 decaying into sulfur. The electrons and neutrinos from this spontaneous decay will share the Q-value as kinetic

energy. The neutrinos cannot be detected, but we can measure the kinetic energy of the electrons and receive an energy spectrum. We can in principle determine the Q-value from the spectrum; the highest recorded energy. But the count rate near the end point energy is small due to noise and background and the limited resolution of the detector, so the value cannot be determined from the spectrum with high enough accuracy. To calculate a better approximation of the Q-value from the electron count rate, the Fermi Theory is used to construct a Fermi-Kurie plot, giving us a linear function, which can be extrapolated. The intersection with the x-axis is the Q-value; in this way the value can be determined more precisely. In order to understand the Fermi-Kurie plot, we have to rewrite Fermi's Golden Rule.

With

$$Q = T_e + T_\nu \tag{2}$$

and

$$E_e^2 = p^2c^2 + m_e^2c^4 = (T_e + m_ec^2)^2 \tag{3}$$

we can write

$$Q - T_e \propto \sqrt{\frac{N(T_e)}{pE_e}} = \sqrt{\frac{N(T_e)p}{E_ef}} \tag{4}$$

where $N(T_e)$ denotes the number of electrons as function of the electron kinetic energy, T_e, $f = 1.3604A^2 + 0.1973A + 0.0439$, and $A = pc/m_ec^2$ is introduced in the function to correct for the Coulomb interaction between the electron from the decay and the daughter nucleus. The Q-value can now easily be obtained by plotting $Q - T_e$ against T_e, which is the Fermi-Kurie plot.

5 The detector and the experimental equipment

A plastic scintillator is used for detecting the radiation. The incident radiation interacts with the plastic molecules and excites them. A molecule can be excited in two ways: firstly, electrons in the atoms can be excited to higher states ($\sim 1eV$); and secondly, the atoms in the molecule can vibrate to higher excitations ($\sim 0.1eV$). The molecule deexcite with the emission of visible light, which is not energetic enough to excite further atoms; the material is transparent to its own radiation, see Fig. 1.

The light from the molecular deexcitation strikes a photocathode and release one or more photoelectrons per photon, called *secondary electrons*, via Compton scattering. See Fig. 2 for the experimental setup. The secondary electron are accelerated and multiplied in a photomultiplier tube (PMT) containing dynodes at different potential. The PMT hence produce an output voltage pulse, where the amplitude of the pulse is proportional to the number of scintillation events, which in turn is proportional to the energy deposited by the primary ionization. To keep this proportionality, the transparency mentioned earlier is necessary.

The PMT only delivers a few electrons per event. The signal therefore needs to be amplified. Firstly, the signal is converted from a current to a voltage pulse in the preamplifier, with a typical size of $\sim mV$. Secondly, the pulse is amplified in the main amplifier, where the signal go from $\sim mV$ to $\sim V$. The pulse is then analyzed in the MCA, where it is digitized and stored in channels which can be displayed on a computer screen.

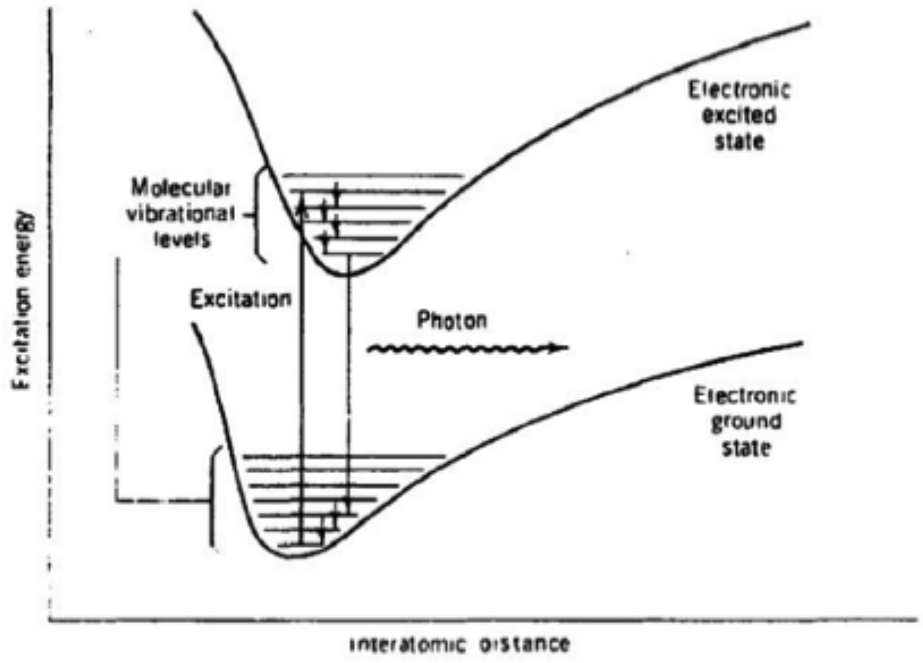

Figure 1: Energy levels in plastic molecules.

To be able to translate the detected signal to the electron energy, the detector must be calibrated with the help of detecting radiation with known, discrete, energies from ^{207}Bi and ^{137}Cs.

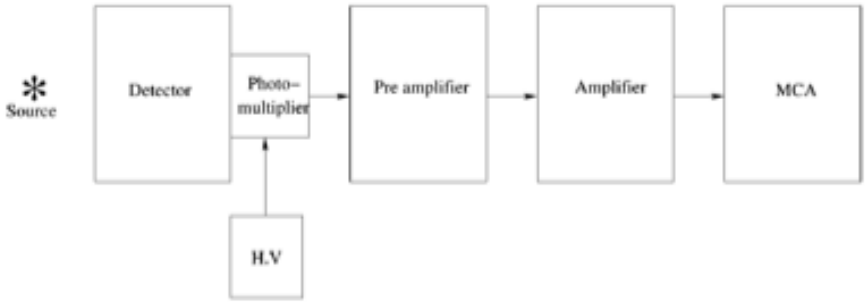

Figure 2: The experimental setup.

6 Warm-up questions

1. Why is ^{32}P a suitable sample to use in this laboratory exercise?
2. How does the electron energy spectrum look like for a β^- decay? Why?
3. Why must the proton undergoing β^+ decay be bound to a nucleus?
4. Calculate the Q-value for the process $^{32}P \rightarrow ^{32} S + e^- + \bar{\nu}$. Hint: you can neglect the neutrino mass and the difference in binding energy of the electrons, why?

5. Why can we neglect the recoil energy of the daughter particle?
6. By what mechanisms does a photon/charged particle lose energy when traversing material?
7. Why is plastic a good material for a scintillator? What properties can you think of that are important to consider?

7 The morning: measure Q value of the β decay of ^{32}P

This part of the laboratory exercise is going to be "guided" yet interactive. Please see section 7.1.1 for what you need to run the analysis on your own computer as we go through the measurement steps.

This is the rough outline:

1. Measure ^{32}P
   - Discuss: How long should the measurement run? Does the spectra look as expected? Is this all we need to determine Q?
2. Measure some more?
   - ^{137}Cs?
   - ^{207}Bi?
   - add shielding to the above?
   - leave the source out completely?
3. Analyse the results!
   - Plot the measured data
   - Calibrate the detector
   - Correct data for background
4. Construct the Fermi-Kurie plot and determine Q
5. Discuss the result and compare to expectation – and where to go from here?

7.1 Data Analysis

The "online" visualization that the Maestro MCA software allows is very helpful but limited and tedious to use for multiple data samples – no way around writing our own code!

Lucky for you, pretty much the whole analysis is already coded and uploaded to `https://bitbucket.org/hperrey/betalab_analysis`. The next sections explain what is needed in order to run the analysis and how to do so.

7.1.1 Prerequisites

The analysis is written in Python3 with the SciPy library[1] for scientific computing – it's all open-source, doesn't cost anything, available for all major platforms and highly flexible; and the key packages are just a download away: Anaconda[2] provides the complete toolkit we need.

If you want to hack around in the code, it might be useful to install `git` as well, a source-code version control tool (never to early to learn git. . .): `https://git-scm.com/`. It is incredibly useful when collaborating on code or (LaTeX) documents and allows to track and merge changes easily. A powerful tool well-worth looking into – there are lots of tutorials[3] online.

7.1.2 Running the analysis

Download the code from `https://bitbucket.org/hperrey/betalab_analysis` into a directory of your liking or clone the whole repository with `git` (if installed previously) by running

```
git clone https://bitbucket.org/hperrey/betalab_analysis
```

on the command prompt (also called *Terminal* or *Konsole* depending on the OS).

Use the development environment of Anaconda (called "Spyder") or a text editor with syntax highlighting of your choice (or ask the supervisor for recommendations) and open the file `analysis.py`.

Now enter the directory and actually run the central analysis by executing `analysis.py`, e.g. by using the "Run" command of Spyder or by entering

```
python analysis.py
```

in a terminal (depending on your installation that might have to be `python3` instead).

Now you should see a little plot with some text in it – and you are all set for the lab!

8 The afternoon: a choice of further studies

- Prepare to report your findings *in a way that the whole group can understand*: what have you been doing, and why? What to make of your result? How does it tie in with the experiment and with the activities of the others?
- Feel free to give this a personal touch and to diverge on things you have discovered or learned along the way – the presentation will be informal in style.
- Keep notes! Make pictures! Think of a joke to tell!
- But informal presentation or not: make sure that you have relevant numbers and parameters of your measurement written down!

[1] `http://www.scipy.org`

[2] `https://www.continuum.io/downloads`, choose the version for Python 3.X.

[3] e.g. `https://help.github.com/articles/good-resources-for-learning-git-and-github/`

- If you don't finish the project or something does not work: don't worry! That's life as an (experimental) physicist... Document your findings and explain what went wrong to your colleagues so that they (or you) don't make the same mistake again.
- There is overlapp between the different topics – embrace it and discuss among your colleagues!

8.1 Uncovering Uncertainties

In order to interpret any measurement result, one has to fully understand the associated systematical (and statistical) uncertainties.
Mission: Quantify the uncertainty of the Q value measurement.
Hints:

- What are *possible* sources of systematic uncertainties? Which ones are actually *likely*?
- Which sources of uncertainty do you expect to contribute the most?
- How can you access these sources of uncertainties? I.e. by what method/variation could you estimate their impact?
- What backgrounds do you expect to have? Take measurements, and analyse the background's energy spectra – how can we reduce or compensate for these backgrounds?
- Use the analysis code to run variation of the input data through – what is the effect on the final result?
- By what systematic procedure could one estimate the dominating uncertainties and quantify them? Try it!
- How do your colleagues investigations tie into systematic uncertainties of the experiment?

8.2 Calibrate for better results

Any detector is only as good as its calibration. By improving the method and/or using additional data points in the calibration, we can improve on the accuracy of the measurement (and get a handle on the uncertainties associated with the calibration).
Mission: Improve the energy calibration of the experimental setup.
Hints:

- There is another source with known peaks from internal conversion electrons available to collect data from: bismuth-207 (^{207}Bi).
- Are you satisfied with the data from ^{137}Cs?
- How can the peaks be more precisely determined?
- Does the background subtraction work as expected?

- Are all data points (i.e. peaks) equally precise? How could you weight their impact on the calibration?
- Should you exclude some points from the data?
- What is the impact on the calibration (and the Q value) if you vary the input data and/or method?
- In an ideal laboratory, how would you want to improve the calibration further?

8.2.1 Energy calibration

Some information that might be useful to extend the energy calibration: Table 1 shows the energies of electrons released from internal conversion for bismuth-207 and the relative intensities.

Table 1: Energies and relative intensities for internal conversion electrons of ^{207}Bi (useful information in the detector calibration).

Shell	E_e (MeV)	I
K_1	0.483	1.55
L_1	0.555	0.45
M_1	0.568	0.15
K_2	0.976	7.05
L_2	1.049	1.85
M_2	1.062	0.60

8.3 One person's background is another one's data

Mission: Using plastic scintillator detectors, study the background due to cosmics.
Hints:

- There are two large pedal plastic scintillators with PMTs available – use this as cosmic ray detector. What geometric arrangement is best suited for such a measurement?
- **Important:** Before moving or connecting the pedal detectors to HV, consult the supervisor and discuss the necessary steps with them! The PMTs can only take negative (-) 1500V *maximum*. Do not go beyond -1300V before discussing this with the supervisor!
- Use a scope to study the signals coming from the scintillators; what do they look like and how do they vary from a source's signal? What is the energy that we expect from cosmics?
- We have several NIM electronic modules to construct a simple counter with: discriminators, coincidence logic, and visual scaler. Research how these function and how to connect them together.

- Determine the count rate and estimate the rate seen in the detector used for measuring the Q value – how much do cosmics contribute to the background and over what energy region? What could one do to shield them?

8.4 Open-signal surgery

For the measurements performed in the morning, we used an MCA to give us pulse-height spectra. However, what do the signals from the actual detector look like that yielded these spectra?
Mission: Connect a scope to the PMT and study its signals. Try to understand what you see.
Hints:

- The scope supports to save waveforms/images – a good way to keep record of your findings.
- Trigger on signals of various heights; does their shape change at all? Can you estimate how fast do those signals come in? Note amplitude and duration of the signals.
- Can you relate what you see to the spectra we measured?
- Do you notice anything unusual? Save those waveforms! What could be the origin?
- How do the signals change with source? Or with the amplifier settings? Or with high-voltate to the PMT? (**Attention:** Do not change the HV before consulting your supervisor!
- Measure the signal coming directly from the PMT – how does it differ from the amplifier signal? What is the ratio of the (maximum/typical) amplitude?
- Do you notice any electronic noise? How do the pre-amp settings influence this?

9 Late afternoon: Concluding discussion and presentation of findings

- Motivate your steps – what provides your project to the experiment?
- Keep it simple – everyone should understand and follow what you have been doing.
- Try to relate what you have learned to the projects of others.
- Stay away from any presentation software – think more show-and-tell/whiteboard/simple picture show instead of elaborate slide show.

A Final discussion points

Teachers notes/suggestions only – ask away if you wish!

- What have we learned more since the measurements this morning?
- Were any of the results particularly surprising for you?
- Are we now ready to publish the results? What would we have to do further?
- With all we know now, what would you do to improve the experiment? Where do you see limiting factors to its precision?

B Feedback

Please fill out the following set of questions and hand them in (anonymously) to the supervisor. Feel free to leave the manual as a whole should you have noted any corrections/suggestions in it!

- What was your favorite part of the lab exercise?

- What was your least favorite part? Why?

- What information would liked to have had *before* the lab?

- What information did you miss *during* the lab?

- What do you feel you have learned from the lab?

- Any more comments or suggestions?