SOLVING A CONUNDRUM IN β-DECAY SPECTROSCOPY EXPERIMENTATION

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Experimentation on beta spectroscopy introduces the student into the field of radioactive decay, the Fermi theory, special relativity and the weak interaction. With the help of a simple surface barrier detector-spectrometer, the continuous spectra of some beta-ray emitters have to be measured and interpreted. Here we show how students react to an unexplained difference between measurement and theory, which leads them to speculate in the end about each possible aspect that may account for it.

Key words: β-decay spectroscopy, quantum physics, scientific method.

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1. INTRODUCTION

Usually in experimental physics in undergraduate courses, the difference between a measured quantity and the theoretical value is always explained in terms of propagation of errors. In the worst case, the difference is attributed to a systematic error. When experimentation is more advanced, like in nuclear physics, errors of course do exist but it is more difficult to propagate them.

In the present work, we present a real situation where students in the laboratory have to perform some practices related to β^--spectroscopy. At some point, they encounter a situation they cannot explain, and the way they have to sort things out become the essential part of their experimentation and of the evaluation of their work.

We shall first provide the basics of beta-decay physics. The experimental setup and how students must proceed is explained in detail. The corresponding explanations for unexpected results are then listed. Finally some conclusions are drawn.

2. BASICS OF BETA DECAY

Beta-decay was first successfully explained by Fermi [1]. Wolfgang Pauli postulated in 1930 the existence of the neutrino to explain the continuous distribution of energy of the electrons emitted in beta-decay. Only with the emission of a third particle would make the preservation of momentum and energy hold. By 1934, Enrico Fermi had developed a theory of beta decay to include the neutrino, presumed to be massless as well as chargeless.

The process of β^- disintegration it has to be interpreted as the spontaneous transformation of one neutron into a proton, releasing one electron and an electronic antineutrino

$$ {}^{A}_{Z}X \longrightarrow {}^{A+1}_{Z}Y + e^- + \bar{\nu}_e \tag{1} $$

In the language of the weak interaction force between quarks [2], one quark d transforms into a quark u. Thus, a neutron converts into a proton

$$ n(udd) \longrightarrow p(uud) + e^- + \bar{\nu}_e \tag{2} $$

Internal conversion (IC) [2] is a radioactive decay process wherein an excited nucleus interacts electromagnetically with one of the orbital electrons of the atom. Thus, in an internal conversion process, a monoenergetic electron is emitted from the radioactive atom, but not from the nucleus. During IC, the atomic number does not change (as is the case with gamma decay) and no transmutation of one element to another takes place.

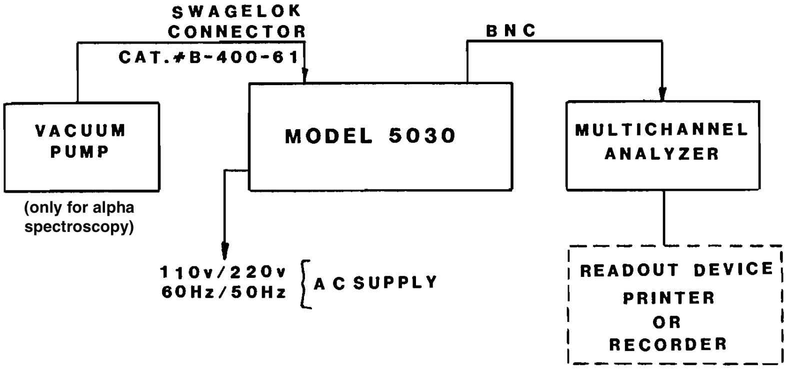

Fig. 1 – Experimental set-up. See text for details.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experimental set-up is shown in Fig. 1. A Model 5030 (the Nucleus©INC.) alpha-beta spectrometer is connected to a 1024-multichannel analyzer, which in turn is connected to a computer. Semiconductor detectors are most commonly used when best energy resolution is intended [3–5]. However, surface barrier detectors like Model 5030 (50 mm^2, +400 V bias tension) are ideal for undergraduate level modern physics laboratories just beginning alpha-beta spectroscopy experiments (with reasonable precision) yet is also a research grade instrument meeting requirements of environmental spectroscopists. No pump is needed for electrons almost do not interfere with air, as opposed to α-particles.

The goals that the student has to reach in the laboratory are:

- Calibrate the spectrometer via PULSER, every 0.1 MeV, from 0 to 1 MeV.
- Analyze the spectrum of ^{204}Tl. With a half-life of 30.08 years, it decays into ^{204}Pb via β^- (97.1%) with a maximum energy $Q_{\beta^-} = 0.7637$ MeV.
- **Obtain the maximum energy Q_{β^-} of ^{204}Tl.**
- Analyze the spectrum of ^{137}Cs and **obtain precise energy peaks** due to IC.

3.1. SPECTRUM OF ^{204}TL

The sources characteristics used are the following: initial activity of 1 μCi for ^{204}Tl (July 1996) and 9 μCi for ^{137}Cs (1982). In the case of *detecting* energy lines no study of present activities has to be performed. The student realizes by calibrating the spectrometer ”artificially” that no sources of monoenergetic electrons exists in nature.

After 24 h collection of data, the raw spectrum counts vs. channel is obtained. Fig. 2 depicts the actual Model 5030, the calibration energy-channel and the typical continuous β^- spectrum for ^{204}Tl. Lorentzian functions are used and precise channel numbers obtained. Once we read in the computer the actual number of counts vs. energy in MeV, we can adjust the spectrum to look like a straight line according to Fermi theory (the so-called Kurie plot). The task of converting the spectrum into a straight line depends on the regions of the spectrum that the students select. Therefore, several attempts are carried out. A typical series obtained is (pairs of Q_{β^-} in MeV and linear correlation coefficient R): $\{$0.62820, 0.99857; 0.62709, 0.99878; 0.63228, 0.99833; 0.63064, 0.99830; 0.62291, 0.99893; 0.62433, 0.99891; 0.62774, 0.99871; 0.62635, 0.99890$\}$.

The student has to decide here that since the calibration is error-free (the precision of the spectrometer allows that), a purely statistical error has to be attributed to the finding of the maximum energy of Q_{β^-} for ^{204}Tl. Thus the student concludes that

$$Q_{\beta^-} = 0.627 \pm 0.005\, MeV \tag{3}$$

Thus, one has to cope with an energy difference with respect to the real expected value of 0.137 MeV. Here is where the student realizes that there is a serious problem: a difference of 137 keV cannot be explained based on a detail detection analysis. There is no activity involved nor geometry of the setting or any other factor that can account for that considerable energy scale in beta spectroscopy. The student is facing a conundrum.

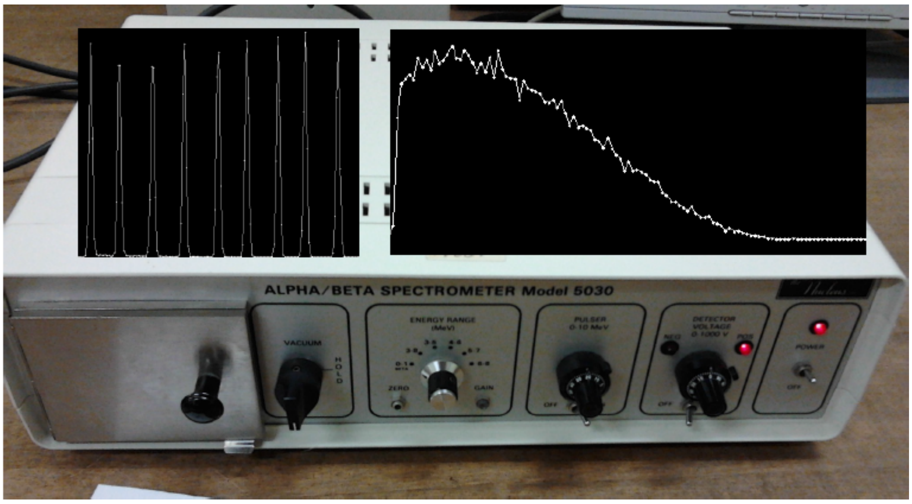

Fig. 2 – Actual picture of the beta spectrometer. The calibration is performed using several known pulses of energy. The complete continuous spectrum for ^{204}Tl is also shown (after 24 h). See text for details.

3.2. SPECTRUM OF ^{137}CS

The characteristics of ^{137}Cs are shown in the half-left part of Fig. 3. ^{137}Cs is a purely artificial isotope that is one of the main targets in the surveillance of tolerable levels of natural radiation, and is also used in calibration for γ-spectroscopy. As far as beta-emitters are concerned, the concomitant spectrum corresponds to a superposition of two β's with different maximum energies. The corresponding spectrum is shown in Fig. 3. However, if a sufficiently long detection is carried out (24 h in our case), small peaks can be detected (emitted with low probability) that are related to a process of IC. In fact, by measuring the energy of these monoenergetic electrons and knowing the outcomes of the IC process, the energy of electron inner shells (K or L) can be measured.

Fig. 3 shows the schematics of the ^{137}Cs disintegration. ^{137}Cs decays to metastable ^{137}Ba via β^- 94.6 $\%$ of the times, whereas it can also decay to the ground state ^{137}Ba also via β^- 5.4 $\%$ of the times. In 86 $\%$ of the cases the metastable ^{137}Ba decays directly to the ground state emitting a photon of 662 KeV. However, the remaining 14 $\%$ corresponds to a IC process, where the energy is transferred to electrons of lower shells (K or L). The binding energy of these levels can be obtained by measuring the kinetic energy of these monoenergetic electrons and subtracting the energy of the photon.

The measured position for the peak K is 645 ± 5 keV. By taking into account the relation between maximum energies and the emitted γ energy of $E_\gamma = 662$ keV, we thus obtain that E_K should be around 16 keV, which is far away from the expected result of 37 keV.

As expected, there is no reason why the obtained result should differ so much from the expected one. It is at this stage that the student becomes really puzzled.

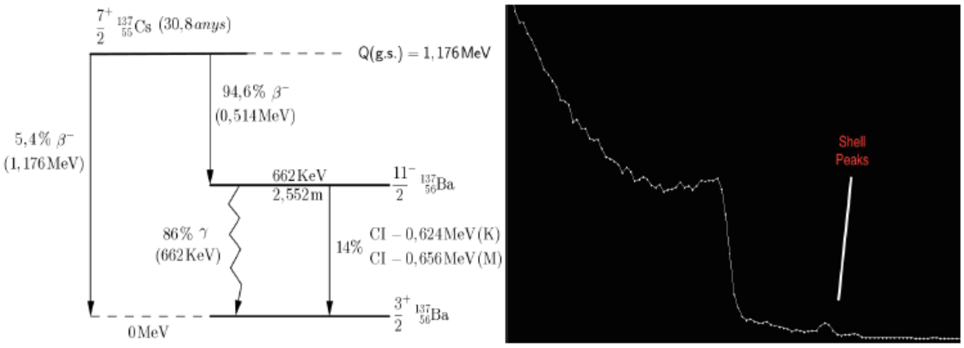

Fig. 3 – Schematics of the ^{137}Cs desintegration and its corresponding continuous spectrum. See text for details.

4. THE CONUNDRUM ”WHY THE MISMATCH IN $E_{\max}$?” AND POSSIBLE ANSWERS

Once the β-spectrometer is calibrated, one expects the measures to be exact to a certain degree of accuracy. Two independent experiments, namely, i) measurement of the maximum energy of ^{204}Tl and ii) measurement of monoenergetic electrons from IC, lead to the same wrong answers. Thus, uncorrelated experiments being both wrong but sharing the same calibration can only mean one thing: there is a systematic error not considered.

The bottom line here is the quest for knowledge by setting a systematic procedure involving the identification of the problem, experimental acquisition of the data, and finally a means, based on the collected data, to examine the assumptions, models and hypothesis. This procedure is what we understand by the *scientific method*. Even though some scientific findings were achieved accidentally, the scientific method dominates most of the scientific activities. Obviously, the most important ingredient of the scientific method is the measurement, as the students may face in the present situation. Thus, the research problem in this paper is concerned with the investigation of the student impression about the implementation of the scientific method to acquire and analyze data from beta spectroscopy experiment. Here we show how students react to an unexplained difference between measurement and theory, which leads them to speculate in the end about each possible aspect that may account for it.

The possible explanations are given by students:

1. There is a systematic error in the measuring process The student considers the energy difference in Q_{β^-} for ^{204}Tl as an overall offset, to rescale results. However, the outcome in obtaining the peaks K or L fails dramatically

2. There is a systematic error due to background radiation The spectrum of the background has to be considered, but the effect is so minor that it is almost irrelevant

3. There is systematic error that occurs in the source This is the only option left. Here, some students argue that the recoil energy, considering a process where the anti-neutrino has almost zero energy, is responsible for the ”missing” energy. However, the correction is so small that it is disregarded. The final answer, which is the one assumed by the instructors to be the correct one and almost never considered by the students, is that absorption occurs already in the source. Commercially radioactive isotope sources come with the shape of a thick coin. The 4-5 mm height of these disks may absorb some part of the energy of the electrons, since no absorption occurs in the air

This last possible explanation can provide a solution to the conundrum, which has repeated itself during different courses.

5. FINAL REMARKS

We have shown how a student performing a practice in β^--spectrometry realizes the nature of a problem with a quite elusive answer. It is not the final outcomes matching the desired values that is appreciated here. Having a difference between measured results and expected results will be indeed be found, and the student has to be able to explore all possibilities to reasonably explain an experimental conflict.

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