Measurement of β-ray spectra

Ana C. Fabela Hinojosa
School of Physics and Astronomy, Monash University

Experiment performed: Tuesday 18$^{\text{th}}$ August, 2020

Abstract

Using a thin lens magnetic spectrometer, we measure the momentum spectrum of electrons emitted as β^- rays from a radioactive source of ^{137}Cs. The detected momentum of the radiated electrons is defined by the spectrometer's adjustable magnetic lens current and k a proportionality constant dependent on the geometry of the apparatus. The magnetic field of the lens is varied by changing the current passing though the lens coil which has the effect of modifying the trajectories of the electrons, focusing electrons with specific momenta onto the detector allowing us to measure their intensity. By converting the measured momentum to energy we are able to fit our data to a linear model based on the Fermi-Kurie plot. We find that the value of the kinetic energy of the nuclear transition is $T = 0.520 \pm 0.044$ MeV which is in agreement with the accepted value of $T = 0.512$ MeV[1].

1 Introduction

When Henri Becquerel first observed $\beta-$radiation, he determined that the observed radiated particle satisfied the same mass-to-charge ratio as the electron, discovered in 1897 by J.J Thompson[2].

Later experimental results showed that $\beta-$rays are detected with a continuous range of kinetic energies up to a maximum value[3]. The discovery of a continuous distribution of electron kinetic energies rather than a discrete predictable value led Wolfgang Pauli to propose in 1930 that the observed violation of conservation laws must be due emission of a yet unknown particle.

In 1934 Enrico Fermi called this apparently massless and undetectable particle the "neutrino", developing an advanced theory of beta decay. The neutrino was finally experimentally observed 1956.[4]

The process we currently know as β^- decay describes a neutron in a parent nucleus desintegrating into a proton in a daughter nucleus, an electron and an antineutrino.

In a β^-event, both nuclides (nuclear species) have the same number of nucleons. This means that the daughter nucleus will not experience a substantial change in kinetic energy (recoil) due to the decay event. Leaving most of the desintegration energy available to be carried-off by the leptons as kinetic energy.

A parent nucleus has a given initial energy w. The avalilable kinetic energy of the system is equal to the decrease in mass energy due to the creation of the radiated leptons:

$$T = w - mc^2, \tag{1}$$

where m is the difference in mass between the daughter and parent nuclides.

The observable count of β^-electrons as a function of energy is now described by the Kurie–Fermi Theory of β^-decay.

2 Theory

In this experiment we measure the momentum spectrum of emitted $\beta-$rays from a radioactive source of ^{137}Cs into an excited state of ^{137}Ba. This transition occurs with a probability of 94.6% at a maximum energy value $T = 0.512$ MeV.[1].

Our experimental apparatus is a thin magnetic-lens spectrometer. The operation of β spectrometers depends on the behaviour of electrons subject to magnetic fields. The magnetic field of the spectrometer lens is varied by changing the current passing though the lens coils. Modifying a cone of electron trajectories diverging from the source along the spectrometer's axis, causing them to spiral around the axis of the instrument towards detector[1]. The trajectories of the electrons are controlled in this way due to the magnetic force:

$$\vec{F_B} = e^- \vec{v} \times \vec{B}, \tag{2}$$

A set of electrons with a specific momentum range is focused onto the spectrometer detector, while electrons outside this range undergo chromatic aberration.

The momentum of the focused electrons is rigorously proportional to the axially symmetric magnetic field.

$$p = e\rho B, \tag{3}$$

where B is the magnetic field strength, e is the electron charge, ρ is the gyroradius of the particle due to B.

Given the lack of ferromagnetic materials, the magnetic field is proportional to the adjustable current I_{lens} going through the lens coils.[5]

The magnetic rigidity P is a measure of the momentum of the particle[6]:

$$P = B\rho, \tag{4}$$

From this relation and the definition of the momentum above, we write:

$$P = kI_{lens}, \tag{5}$$

where k is a constant determined by the geometry of the spectrometer alone[5].

2.1 Calibration

Calibrating the observed momentum distribution requires us to use electrons that are emitted with a characteristic well-defined kinetic energy known as conversion electrons[1].

In this experiment we study the most probable energy transition from ^{137}Cs to ^{137}Ba. The daughter nucleus in this scenario is in an excited state. One way for the atom to lose energy is by transferring the excess energy directly to an orbital electron[1]. The orbital will most likely be the K-shell since it is the lowest energy orbital. A higher energy group event is much rarer with a probability of 6%. Therefore little error is made by assuming that the peak is due to the K line only.[1].

The constant k in (3) is determined by calibrating the observed spectrum to the well-known K-conversion peak with kinetic energy $T = 624.21$ keV.

The resolution of the spectrometer used in this experiment is constant $(2 - 3\%)$.

References

[1] Monash SPA. 4.4 measurement of β-ray spectra, 2020.

[2] Wikipedia. Beta particle, 2020.

[3] C A Moyer R A Serway, C J Moses. *Modern Physics, third edition.* 2005.

[4] Carl R Nave. Beta radioactivity, 2001.

[5] D Halliday EA Quade. A magnetic lens beta-and gamma-ray spectrometer, 1947.

[6] Wikipedia. Rigidity (electromagnetism), 2019.