ENERGY SPECTRUM OF A BETA RADIATION SOURCE

INTRODUCTION

Most experiments on radioactivity deal with the absorption properties of materials without illustrating the quantitative difference between types of radiation. Beta and gamma radiation are absorbed by matter in a similar, although not identical, manner; beta being absorbed much more easily of course. The two types of radiation have significant differences in that gamma rays or photons have no mass, nor charge and travel at the speed of light, however, beta radiation is composed of electrons with charge, mass and finite speeds. Although these differences may not be of great importance in some radiation experiments, they do have a great effect on how the two types of radiation interact with matter. We will use a beta spectrograph to show the difference between these radiation types.

ENERGY SPECTRUM

So you may wonder what a beta energy spectrum is. Simply put, it is the intensity of the beta beam at different particle energy. The intensity is proportional to the number of counts registered by the Geiger counter while the energy of the beta particles can be derived from the angle by which they deflect under a magnetic field.

In this lab, beta particles from a source are collimated and directed through a magnetic field provided by a pair of ceramic magnets, which deflect them into a detector. The beam deflection varies from 0° to 90° depending upon the energy of the particles as shown in Figure 1. The beam intensity is measured by a Geiger tube mounted in the magnet support structure. The source is mounted on a rotating arm so that the beam passes through the magnetic field and enters the Geiger tube through an aperture in the cast iron frame. Rotating the arm permits the measurement of the intensity as a function of angle. The deflection angle is inversely related to the energy of the beta particles so that the beam intensity as a function of energy can be determined from the data.
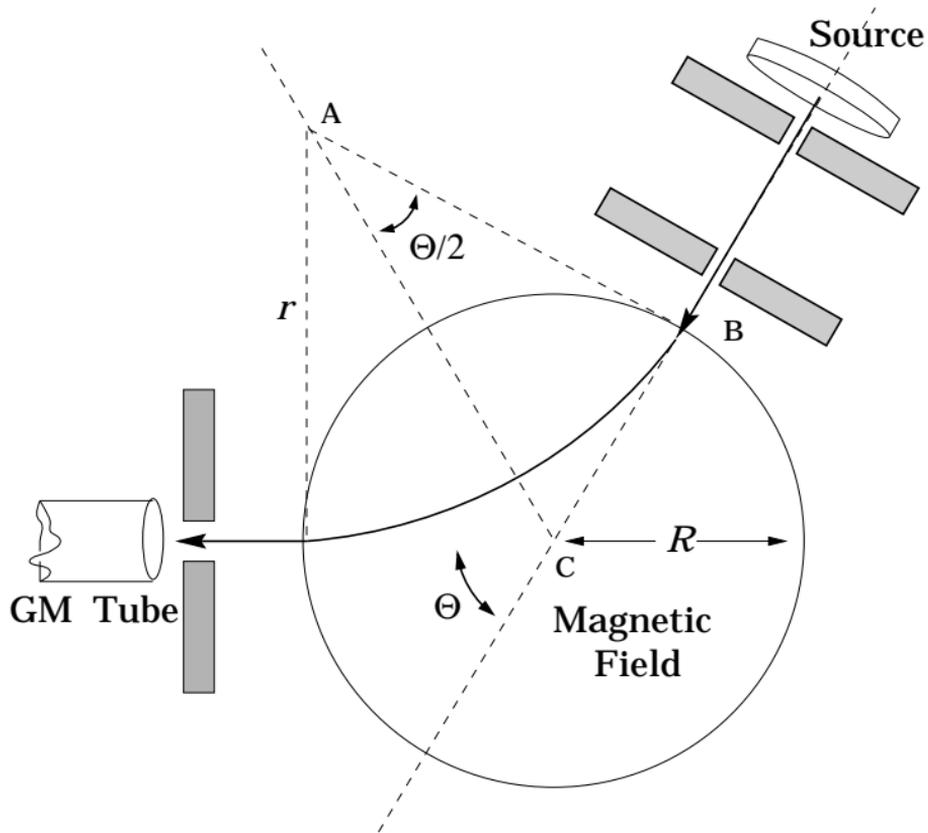
Figure 1   Experimental Setup

OPERATION OF THE EQUIPMENT

For this lab you will need:

        A Geiger Tube
        A Geiger Counter
        Radioactive Sources
        A Computer and Counting Software

Part I in Appendices of the last lab handout, *Geiger-Müller Counters and Radiation Event Counting Software* provides more detail about operation of the Geiger counter and counting software.

1.   Set the magnet frame on a level table with space around it for the other pieces of apparatus. The source should be mounted in the arm. It is attached with double-sided foam tape to the back of the rotating arm. It should be centered on the vertical part of the arm and in line with the aperture in the lead absorber.

Two sources are recommended for use with the apparatus; either Sr^{90} or Tl^{204} give good results. C^{14}, which is a good beta emitter, does not work because its beta particles have low energy and are deflected out of the magnetic field before they can reach the Geiger tube. Since the count rate is much higher with Tl^{204}, it is suggested that this source be used.

2.   Carefully place the Geiger tube into a pocket provided for it in the back of the magnet frame. Don't let the window of the tube touch the end of the cavity. Tighten the nylon screw on the top of the frame to hold it in place.

3.   Connect the coaxial cable of the Geiger tube to the rear BNC connector of the Geiger counter.

4.   Turn on the Geiger counter to the CONTINUOUS mode.

The Counter is continuously active in this mode and should show a few counts from the source or from background radiation.

Make sure all of the connections are correct. The easiest way to do this is to hold a gamma radiation source, if you have one, near the side-wall of the Geiger tube. This will cause the tube to count rapidly and verify that all connections are correct.

To start the measurements, remove the gamma source and anything else that might add to the background count.

5.   Rotate the source arm to 90° to the right.   Using one of the counting
       programs on the computer, record the number of counts detected during a
       three minutes period.

6.   Move the source arm to the 90° left position and repeat the measurement.
       The count rate will be higher on one side than the other.   This will
       enable you to determine in which direction the beta particles are
       deflected.   The deflection is determined by the polarity of the magnetic
       field and the charge on the beta particle.   Can you confirm the polarity
       of the charge on the beta particle?

Now we enter the key stage of this lab, MEASUREMENT OF THE INTENSITY AS A
FUNCTION OF ANGLE. It is convenient to measure the count for 5° increments in
angle. Smaller steps than this are close to the resolution of the apparatus and
waste time. Larger steps have too few points to make a convincing graph.   If
time is limited, 10° steps can be used without too great a sacrifice in
credibility.

7.   Set the Source arm on the side that gives the higher intensity as measured
       in the first part of the experiment. Time the count for 5 minutes.

For weak sources and large angles, the count can be very low so that the time it
takes to collect large counts is quite long.   Since laboratory time is very
limited, it is best to decide on a data collection procedure that can be
completed in the available time. Usually, counting for fixed time intervals is
best, say three or five minutes, so that the total time is predictable even
though the accuracy will not be very high for the low count rates.

8.   Measure the count for each five degrees interval starting at 90°.   The
       count rate will change significantly between settings. Continue until 10
       points have been measured.

9.   Measure the background radiation.   This measurement is important, since
       the background count must be subtracted from all of the other readings.
       Count for at least four times as long as the time period used for the
       angle measurements.   The source arm should be set to 80° on the opposite
       side.   The magnetic field will sweep the beta particles away from the
       Geiger tube so that the tube will be responding to cosmic ray and
       environmental radiation rather than the source.

The background is usually fairly constant for a given Geiger tube and amplifier
in the same environment.   After the background has been measured by several
groups in the laboratory and found constant, its value can be used so that later
measurements are unnecessary, thus saving laboratory time.   It is always safest
to measure the background before and after the measurements, if serious work is
undertaken.

If the EN-30 Precision Geiger Counter is used, all of the measurements can be
made to fixed accuracy.   The Precision Geiger Counter will measure the count

rate for a fixed number of counts. This is very convenient for measurement of the low count rates and background count that can take almost three hours to reach 4000 counts. The EN-30 holds the measured count rate until the operator comes to retrieve it.

Calculation of the Beta Energy Spectrum (from the data)

Plotting the count rate minus the background is the first plot that should be made. It will show if an error has been made and a particular point should be measured again. A sample of data plotted this way is shown in Figure 2. This figure shows two sources, Thallium^{204} and Strontium^{90}, both good sources of beta radiation. It can be seen that the peak intensity for Sr^{90} occurs at a smaller deflection angle than for Tl^{204}. This suggests that the beta particles from Sr^{90} are more energetic than those from Tl^{204}. This is indeed true.

You may find that the points on your curve are more scattered than those in Figure 2. This is because the data are based on the count rate for 4000 counts, so that the points are very accurate, but it took several days to collect the data. You may not have time to use this many counts. The curve is a sample of what you could achieve if you had the time to do it.

A second comment should also be made about the figure. The Sr^{90} source used had only 1% of the intensity of the Tl^{204} source. This does not change the results but it makes the data difficult to plot. To correct this, the Sr^{90} data were increased by a factor that made the two sources have the same apparent intensity.

Of greater interest than the count rate, which is after all only characteristic of the source and the apparatus, is the count rate versus angle which is equivalent to the count rate as a function of energy. It was shown earlier that with a knowledge of the magnetic field, the deflection angle could be used to determine the energy of the particle. The Tl^{204} data plotted in Figure 2 are tabulated in Table 1, together with the energy and the rate of change of energy with angle.

It can be seen from this table that the energy increases with angle in a very nonlinear manner. The energy increase for a change in angle becomes very large, as the energy is greater. Since the geometry of the collimator and collector in the Spectrograph have a fixed collection angle of about 5°, the result is that the range of energies collected for a given angle changes with the angle. The data that has been taken gives the relative amount of radiation directed into each 5° angle increment (0-5°, 5-10°, 10-15°, ...), i.e. counts per Δq. However, our true interest is in finding the beta radiation energy spectrum for the source, i.e. the relative number of beta particles emitted as a function of particle energy. We must transform out data into the form counts per ΔE to

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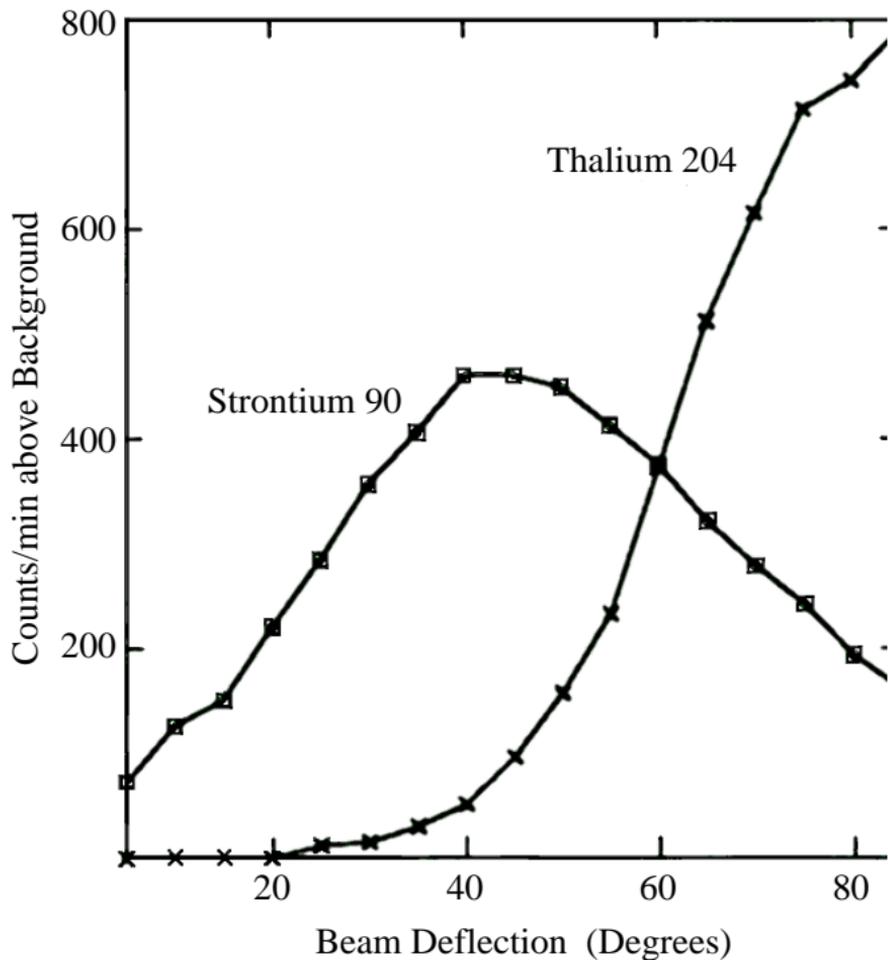
Figure 2   Measured Energy Spectrum of Thallium^{204} and Strontium^{90}

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Source: Thallium²⁰⁹

Background Count: 24/m
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Angle	Energy(MeV)	$\Delta E/\Delta\Theta$ (relative)	Count/min	(C/min-Bkgd)	$\dfrac{\text{(C/min-Bkgd)}}{\Delta E/\Delta\Theta}$
90	.343				
85	.394	.051	816	792	792
80	.452	.058	767	743	657
75	.517	.065	739	715	555
70	.592	.075	639	615	417
65	.679	.087	536	512	300
60	.780	.101	398	374	188
55	.900	.120	258	234	99
50	1.044	.144	183	159	56
45	1.219	.175	121	97	28
40	1.438	.219	77	53	12
35	1.720	.282	55	31	6
30	2.095	.375	39	15	2
25	2.620	.525	35	11	1

Table 1

obtain this information.   Thus we need to multiply each measurement by

$$\frac{\Delta \boldsymbol{q}}{\Delta E(\boldsymbol{q})} \, .$$

The simplest correction has been used in Table 1.   The differences for successive energies in column two are tabulated in column three.   The (Count/min Background) value is divided by this number and then normalized by multiplying by the value for 85°, i.e., .041.   A sample calculation for 50° gives

$$\frac{(183\,\text{Counts/min}\,) - (24\,\text{Background})}{0.144\,(\Delta E/\Delta \boldsymbol{q}\,\text{at}\,50°)} \times 0.051 = 56(\frac{\text{Counts/min}}{\Delta E}) \, .$$

This correction makes the data comparable to other published beta spectrum data. The spectrum of Tl^{204} and Sr^{90} are shown in Figure 3 corrected for constant ΔE by the above procedure.   As before, the Sr^{90} curve is adjusted upward to plot with the Tl^{204} curve.

The most significant characteristic of the beta spectrum is the energy cutoff value. This is the value referred to in tables of energy of beta radiation. From Figure 3, it is clear that most of the energy of the radiation occurs at lower energies than this cutoff value.   The nature of the spectrum was difficult to understand, since there seems to be no other change in the nucleus except that it changes to the next higher positive species.   But if the beta particles emerge with a wide range of energy, how is momentum and spin conserved? Conservation was maintained by the additional emission of a very hard to detect particle, the neutrino, which carried off the balance of the energy and spin.   A beta particle emerging at maximum energy takes it all. For lesser energies, the balance is carried off by the neutrino.   So this little experiment establishes the charge of the beta particle and gives the experimental basis for the existence of the neutrino.

Sections of this Lab were taken from:

Instruction Manual for EN-08 Student Beta Spectrograph , Daedaoln Corporation, 35 Congress Street, Salem, MA

Physics Vol. 2, Tipler, Worth Publishers.
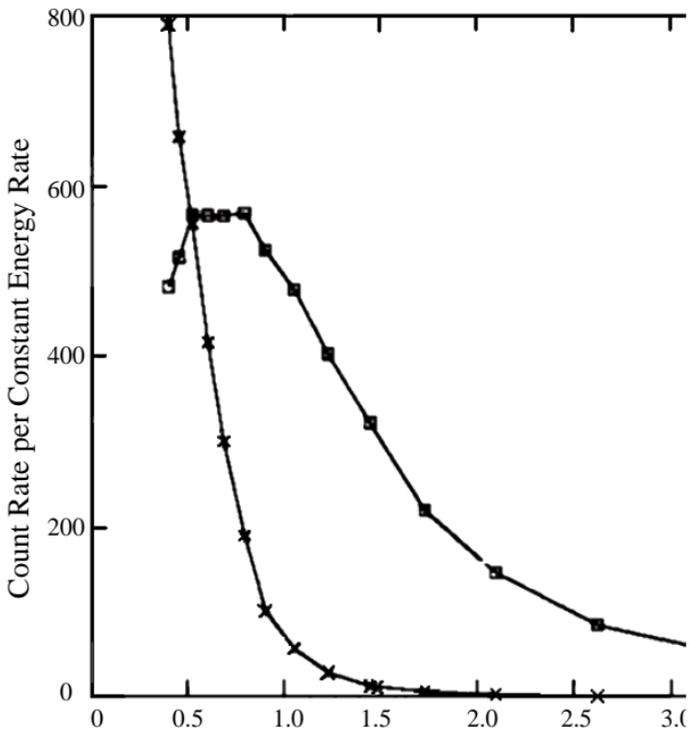
Figure 3   Beta Radiation Energy Spectrums for Tl²⁰⁴ and Sr⁹⁰

The determination that beta radiation consists of charged particles is the most significant conclusion of this experiment because it establishes the nature of this fundamental type of radiation. The measurement of the energy spectrum of the beta particles is of almost equal importance, for the nature of the energy spectrum led to the discovery of the neutrino by Fermi in 1934.

It is intuitively clear that the slower a beta particle is moving, the more strongly it will be deflected by a magnetic field. The path of charged particles of any energy will bend but the radius of curvature will depend upon the energy.

By measuring the strength of the magnetic field and the radius of the path of the beta particle, the energy the particle had can be determined. To derive the required formula, let us start by determining the radius of the path through the field by measurement of the deflection angle. The geometry of the beam passing through the field is shown in Figure 1. The beam enters the magnetic field at point B and follows a circular until it leaves and enters the Geiger tube. The radius of the arc r can be determined from the radius of the field R and the deflection angle.

The angle ACB is seen to be $(180° - \theta)$ $= (90° - \theta/2)$.   Therefore the angle CAB $= (180° - 90° - ACB) = \theta/2$. In the triangle ABC,

$$\tan \frac{q}{2} = \frac{R}{r} ,$$

so that

$$r = \frac{R}{\tan \dfrac{q}{2}} .$$

The total energy of a beta particle is the sum of the potential and kinetic energy and is given by

$$E = \sqrt{(pc)^2 + (m_0 c^2)^2} - m_0 c^2 ,$$

where c is the velocity of light and m_0 is the rest mass of the electron. Dividing through by $m_0 c^2$,

$$E = m_0 c^2 (\sqrt{(\frac{p}{m_0 c})^2 + 1} - 1) .$$

The centripetal force required to keep a particle moving on a circular path is given by

$$F = \frac{mv^2}{r} \ .$$

This force is produced by the charge of the particle e moving through the magnetic field B. so that

$$F = eBv \ .$$

These two expressions for the force are equal so,

$$\frac{mv^2}{r} = eBv \ ,$$

giving,

$$mv = eBr \ .$$

But $mv = p$ the momentum of the particle, so that we can substitute in the energy equation and obtain,

$$E = m_0 c^2 (\sqrt{(\frac{eBr}{m_0 c})^2 + 1} - 1) \ ,$$

and substituting for r,

$$E = m_0 c^2 (\sqrt{(\frac{eBR}{m_0 c \tan \frac{q}{2}})^2 + 1} - 1) \ .$$

All of the quantities in this equation are known or may be measured by our experiment.

For the EN-08 Beta Spectrograph apparatus used in this lab, R = 5.7 x 10^{-2} m and B = 6.9 x 10^{-2} T. The remaining values can be taken from tables of physical constants. Making these substitutions gives,

$$E = 0.511(\sqrt{(\frac{1.34}{\tan \frac{q}{2}})^2 + 1} - 1) \ \text{MeV} \ .$$

This is the required formula relating the energy of the beam in units of MeV, as a function of the deflection angle of the beam for the particular equipment used

in this lab (EN-08 Beta Spectrograph). Remember that this equation is derived from an apparatus that had a field of 6.9 x 10^{-2} T. This value should not deviate strongly from device to device but it would be well to check the assumption. If a flux density meter is available, the field can be measured by placing the probe in the gap between the magnets. Take several measurements and average your results.