Institute for Nuclear Physics, University of Cologne

Practical Course Master

experiment no. 3.4

β scintillation

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Abstract

Energy spectra of electrons from the β decay of ^{207}Bi and ^{137}Cs are measured using a scintillation detector. The (continuous) spectrum of the electrons and the corresponding Kurie plot are compared to the theoretically expected distribution. Contributions coming from conversion electrons of coincident γ decays have to be taken into account.

1 Introduction

During this experiment, the nature of β radiation is investigated. The broad, continuous energy distribution of the electrons emitted from the β decay is measured using a scintillation detector, as well as the conversion electrons stemming from internal conversion.

2 Theoretical basics

2.1 The three components of β decay

The β decay is driven by gaining energy. Following the *droplet model* and the subsequent *Bethe-Weizsäcker mass formula*, this energy gain can be calculated from the differences in the binding energies of the involved parent and daughter nuclei.

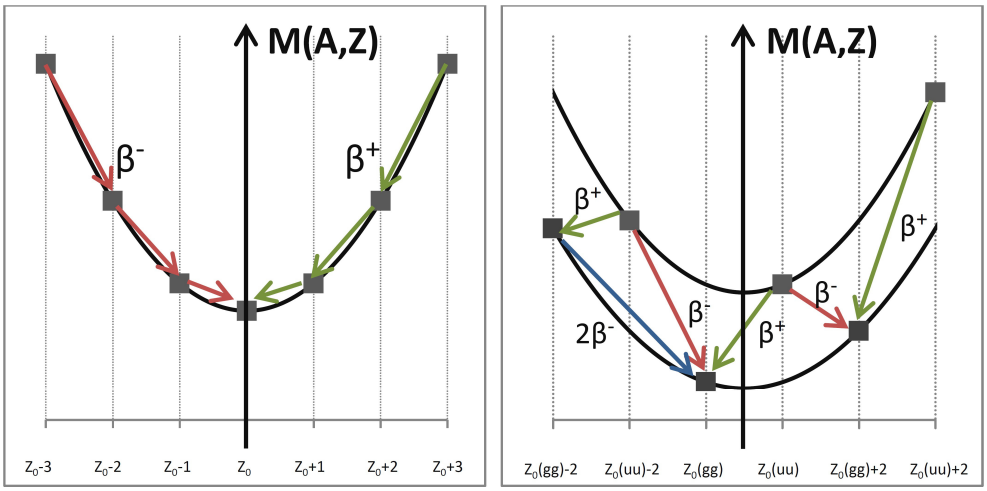


***Figure 1**: Decay parabola for β decays of isobars with uneven (left) and even (right) mass numbers A, see [9].*

Calculating the binding energies for a chain of isobars, i.e. nuclei with $A = Z + N = const.$", as a function of Z, binding-energy maxima appear for certain proton-to-neutron ratios. These nuclei with maximal binding energy also have the smallest mass, due to the relation $E_B = \Delta m \cdot c^2$. Since the effective binding energies in the *Bethe-Weizsäcker equation* show a Z^2 dependence, nuclei

with odd numbers of neutrons or protons (even/odd, odd/even nuclei) in a chain of isobars show a parabolic behavior. For nuclei with even or odd numbers of protons and neutrons (even/even, odd/odd nuclei) two distinct parabola are found due to the pairing term, see Fig. 1.
Nuclei in an isobaric chain with masses higher than the nucleus with the lowest mass (Z_0) are typically unstable. Nuclei with $Z > Z_0$ can convert to nuclei with lower Z via β^+ decays, where a proton is converted into a neutron. The binding energy increases, whereas the nuclear mass decreases. Nuclei with $Z < Z_0$ can analogously convert to nuclei with higher Z via β^- decay. During this decay, a neutron is converted into a proton.

$$ {}^{A}_{Z}\mathrm{X} \xrightarrow{\beta^- - \mathrm{decay}} {}^{A}_{Z+1}\mathrm{Y} + e^- + \overline{\nu}_e \,, $$

where $\overline{\nu}_e$ denotes an anti-neutrino. The neutrino is a lepton just like the electron. Since the lepton number must be conserved and the electron is generated during the decay, an anti-lepton must be formed simultaneously, the anti-neutrino. Both particles are generated during the decay. As both particles have a mass, the energy (or mass) differences of the involved nuclei must be larger than the sum of the rest masses of these particles:

$$ Q_{(\beta^-)} = [m({}^{A}_{Z}\mathrm{X}) - m({}^{A}_{Z+1}\mathrm{Y})] \cdot c^2 > [m_e + m_{(\nu_e)}] \cdot c^2 \quad (1) $$

$$ Q_{(\beta^-)} = m_e \cdot c^2 + E_{kin}(e^-) + E_{kin}(\nu_e) \quad (2) $$

Since the neutrino mass $m_(\nu_e)$ is very small, it can usually be neglected. The energy difference of the aforementioned equation is also denoted as Q value. The amount of released energy is distributed statistically among the decaying nucleus, the electron, and the anti-neutrino. Thus, the continuous shape of the spectra can be explained. The same holds analogously for the β^+ decay. *Chadwick* found in 1914, that during β decay, a continuous energy distribution of the emitted electrons and positrons occurs. This fact could not be explained satisfactorily for a long time, since energy and momentum conservation seemed to be violated. *Fermi* developed a theory twenty years later, which could explain this phenomenon.
Another possibility of conversion towards more stable nuclei, which is also assigned to β decay, is the electron capture ($e.c.$, ε). During this process, an electron of the atomic K shell is captured by a proton in the nucleus. The expectation value of the radial part of the electron wave function in the K is different from zero inside the nucleus, i.e. at $r = 0$. Thus, the electron has a certain probability of presence inside the nucleus, which allows for capturing. The proton is converted into a neutron during the capture of the K electron.

$$ {}^{A}_{Z}\mathrm{X} \xrightarrow{\varepsilon - \mathrm{decay}} {}^{A}_{Z+1}\mathrm{Y} + \nu_e $$

2.2 Fermi theory of β decay

At this point, please refer to the text books *„Kernphysik“*, by *Theo Mayer-Kuckuk* [9] and *„Modern Nuclear Chemistry“* by *Loveland, Morrissey und Seaborg* [8].

In 1934, *Enrico Fermi* postulated a theory of β decay, which could explain the structure of the observed β spectra. It was based on the theory of spontaneous emission of photons of systems in excited states, which was adapted to β decay. The β decay and the emission of photons from excited systems seemed to have not much in common at a first glance. However, in both cases specific systems exist where the potential decay energy could be released via the spontaneous decay and production of one or more particles. Describing this decay process necessitated are purely quantum mechanical approach, as two particles are created during the decay and the energy spectrum of the electrons must obey special relativity due to the relation $Q_\beta \propto m_e \cdot c^2$. The β decay kinematics follows a first-order reaction. Thus, a specific decay can be characterized using a single decay constant λ. The basic equation is given by Fermis *„golden rule"*, which gives the transition probability between an initial state ψ_i and the final state ψ_f^* of the system:

$$\lambda = \frac{2\pi}{\hbar} \Big| \int \psi_f^* \, V_p \, \psi_i \, d\tau \Big|^2 \cdot \rho(E_f) \,, \tag{3}$$

where λ denotes the decay constant of this decay. ψ_i denotes the wave function of the whole nucleus in its ground state in the case of the β decay:

$$\psi_i = \phi_i({}^A_Z\mathrm{X})$$

ψ_f^* is the wave function of the system composed of all generated particles during the decay and, thus, contains parts of the daughter nucleus after the decay, the electron, and the neutrino:

$$\psi_f^* = \phi_f({}^{A'}_{Z'}\mathrm{X'}) + \phi_f(e) + \phi_f(\nu)$$

These three parts of the wave function must be connected in a way, that energy conservation holds. V_p is the perturbation operator of the interaction and shows, descriptively spoken, a minimal perturbation of the system causing the decay. Thus perturbation was assumed by *Fermi* to be different for the β decay than for gravitational, Coulomb, or strong interaction. It described the interaction between the nucleus, electron, and neutrino and is called *„weak interaction"*. Similar to the other three fundamental forces of nature, a constant describing its force can be given. This coupling constant ϱ has the value $0,88 \cdot 10^{-4}$ MeV/fm^3.

$\rho(E_f)$ denotes a function, which yields the density of states which can be reached by the decay. This level density is also often denoted as dn/dE, where n states exists in an energy interval from E to $E + dE$.

The basic ansatz from equation (3) can be factorized in two parts, firstly the matrix element

$$|M_{if}|^2 = \Big| \int \psi_f^* \, V_p \, \psi_i \, d\tau \Big|^2$$

and secondly the level density function of the possible final states

$$\rho(E_f).$$

The level density of final states after the decay can be determined from quantum statistics. The fundamental problem is to estimate the number of possibilities, how the decay energy can be distributed among the electron and the neutrino. First, it is assumed that the recoil of the daughter nucleus can be neglected.
For an electron having a momentum between p_e and $p_e + dp_e$, the following final states in a volume V are possible:

$$dn_e = \frac{V\, 4\pi\, {p_e}^2\, dp_e}{h^3} \tag{4}$$

V corresponds to the volume of a spherical shell in the phase space having the volume of the unit cell of h^3. The same holds true for a neutrino with momentum between p_ν and $p_\nu + dp_\nu$. The total number of possible states is then given by the product of the possible final states of the electron and the neutrino:

$$dn_e = \frac{V^2\, 16\pi^2\, {p_e}^2 {p_\nu}^2 dp_e dp_\nu}{h^6}$$

Assuming that the neutrino mass equals zero, it follows for the neutrino momentum:

$$p_\nu = \frac{Q - T_e}{c}$$

and

$$dp_\nu = \frac{dQ}{c}\,,$$

where Q denotes the decay energy and T_e is the kinetic energy of the electron. By substitution, the following expression is found:

$$\frac{dn_e}{dQ} = \frac{16\pi V^2}{h^6 c^3}(Q - T_e)^2\, {p_e}^2\, dp_e$$

This equation does not give a derivative, but rather the change of possible final states with changing decay energy Q. Combining this expression with equation (3), the following expression is found for the probability λ, that an electron with momentum in the interval from p_e to $p_e + dp_e$ is emitted:

$$\lambda(p_e)\, dp_e = \frac{1}{2\pi^3 \hbar^7 c^3}\, |M_{if}|^2\, (Q - T_e)^2\, p_e^2\, dp_e$$

Let C^2 contain all constants of the aforementioned equation, then the decay probability of a nucleus as a function of the electron momentum can be written as:

$$\lambda(p_e)\, dp_e = \boldsymbol{C^2}\, (Q - T_e)^2\, p_e^2\, dp_e$$

Despite the mixing of momentum and kinetic energy of the electron one can see, that this function goes to zero, if either the electron momentum p_e is zero, or the kinetic energy T_e equals the decay energy Q. A maximum is located in between. This function explains the basic form the spectrum, as shown below in Fig. 2.

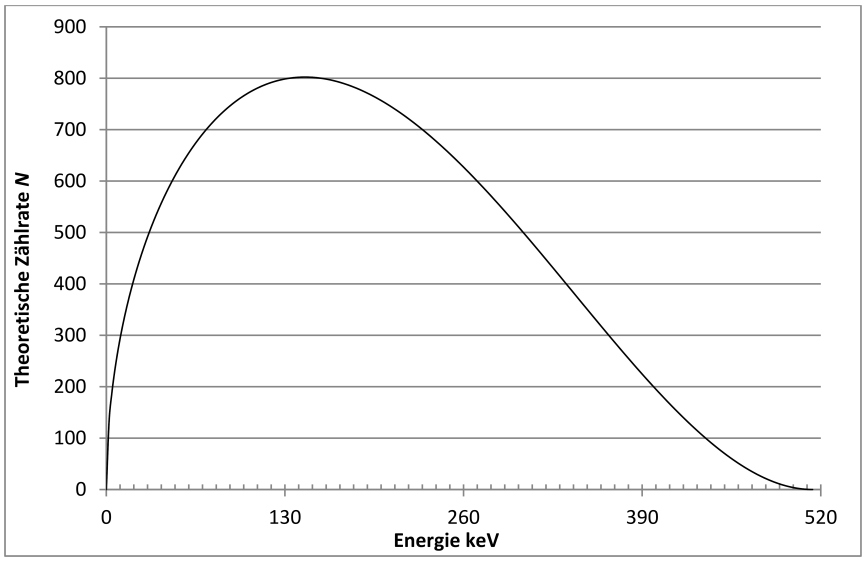


Figure 2: *Calculated spectrum of electron energies of the low-energetic decay of* ^{137}Cs.

During the derivation of this equation, many assumptions have been made. Therefore, the theoretical spectrum does not agree completely with a measured one. For this reason, the equation as derived above must be modified by a correction term.

2.3 Correction with Fermi function

First of all, the recoil energy of the daughter nucleus was neglected. Due to the low mass of electron and neutrino, the energy and momentum transfer on the recoiling nucleus is of the order of approximately 10 eV. The same holds true neglecting the neutrino mass, which only causes a minor deviation. At this point, both influences will not be accounted for, since there is almost no influence on the analysis of the present experiment.
The other assumption that was made, which has a significant influence on the spectrum, is the electric neutrality of the involved particles. Positrons and electrons are influenced by the nuclear charge depending on their kinetic energy. The positive charge of the positron and the positive nuclear charge cause a repulsive Coulomb interaction. Thus, the positron spectra will be shifted towards higher energies. On the other hand, the positively charged nucleus acts attractively on the electrons. Hence, the energy distribution of the electrons is shifted towards lower energies. In both cases, the kinetic energy of the particles determines the time scale in which the particles are exposed to the Coulomb field. Low-energetic particles are exposed to the Coulomb field for longer times and, thus, experience a stronger influence. These electromagnetic interactions are accounted for by the so-called *Fermi function* $F(Z, p_e)$. It depends on the momentum p_e of the electrons and positrons, respectively, as well as on the electric field strength, i.e. the nuclear charge Z. The Fermi function enters the expression for the transition probability as follows:

$$\lambda(p_e)dp_e = C^2 \cdot \underline{\boldsymbol{F(Z, p_e)}} \cdot (Q - T_e)^2 \cdot {p_e}^2 \cdot dp_e \tag{5}$$

Calculating the Fermi function appears to be rather complex, thus, their values are given in tabulated form. For the data analysis of the present experiment, the tabulated results from *Behrens* and *Jänecke* from the text book *Landolt-Börnstein* [1] are used, see Table 2 in the appendix. By taking into account the Fermi function, the theoretical spectrum as shown in Fig. 3 is obtained.

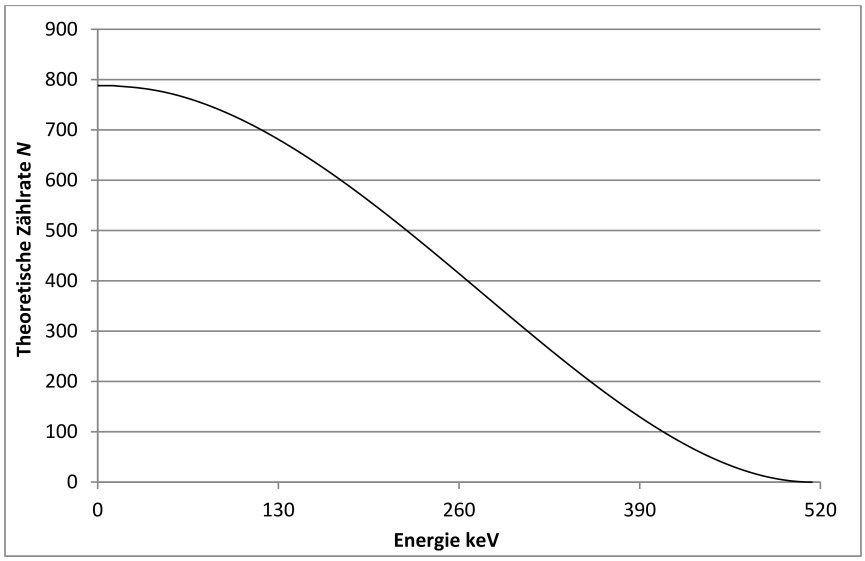


***Figure 3**: Theoretical spectrum of the low-energetic decay of ^{137}Cs corrected by the Fermi function.*

2.4 Kurie-Plot

The maximum of the particle energy from the spectrum equals the Q value. However, the Q value can neither can derived easily from the equation, nor be exactly determined from the measured spectra. This can be accomplished, if the spectrum is plotted as a so-called Kurie plot. For this purpose, the aforementioned equation (5) is rearranged to give:

$$\sqrt{\frac{\lambda(p_e)}{{p_e}^2 \cdot F(Z, p_e)}} = C \cdot (Q - T_e)$$

Since $\lambda(p_e)$ denotes the probability, that an electron with momentum p_e is emitted, it can be replaced by the intensity or count rate of the respective electron events $N(p_e)$. Under the additional assumption, that the matrix element contained in the constant C does not influence the kinetic energy of the electrons, on the left hand side the reduced spectral distribution of the intensities, and on the right hand side, the kinetic energy of the electrons is given.

$$\kappa(p_e) = \sqrt{\frac{N(p_e)}{{p_e}^2 \cdot F(Z, p_e)}} = C \cdot (Q - T_e) \tag{6}$$

Following *Mayer-Kuckuk* [9], it is useful to measure energy and momentum in terms of natural units of $m_0 \cdot c^2$ and $m_0 \cdot c$, respectively. The relations for the kinetic energy are:

$$\epsilon = 1 + \frac{T_e}{m_0 \cdot c^2}$$

and

$$\epsilon_0 = 1 + \frac{Q}{m_0 \cdot c^2}$$

For the momentum:

$$\eta = \frac{p_e}{m_0 \cdot c}$$

This presents the advantage, that equation (6) using the relation $\epsilon^2 - \eta^2 = 1$ can be transformed to expressions, which only depend on energy or momentum:

$$\kappa(\eta) = \sqrt{\frac{N(\eta)}{\eta^2 \cdot F(Z,\eta)}} = C \cdot (\sqrt{1+{\eta_0}^2} - \sqrt{1+\eta^2}) \tag{7}$$

$$\kappa(\epsilon) = \sqrt{\frac{N(\epsilon)}{\epsilon \cdot \sqrt{\epsilon^2-1} \cdot F(Z,\epsilon)}} = C \cdot (\epsilon_0 - \epsilon) \tag{8}$$

Plotting the reduced spectral intensity distribution $\kappa(\epsilon)$ over the relativistic energy ϵ, one obtains in case of a pure β spectrum a straight line in this representation. The intersection with the x-axis then yields the maximum of the kinetic energy of the electrons.

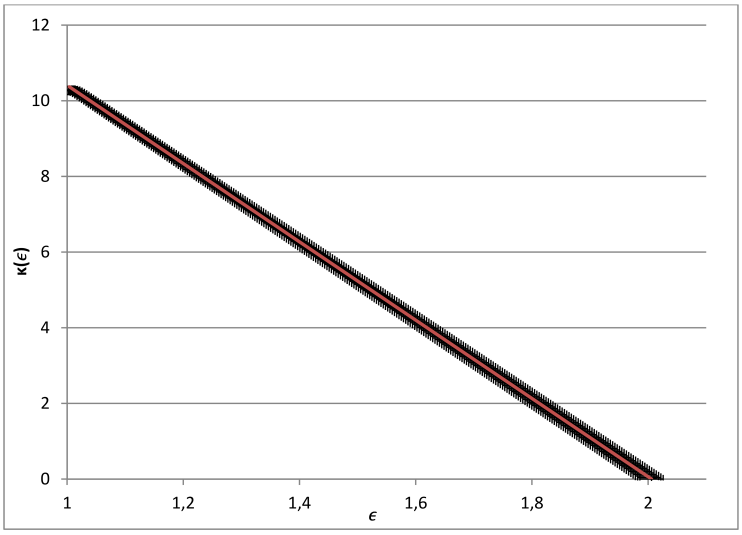


***Figure 4**: Kurie plot of the theoretical electron spectrum of the low-energetic decay of ^{137}Cs.*

In this way, the electrons maximum energy should be determined from the ^{137}Cs spectrum during the data analysis. However, due to two competing decays and the conversion electrons, not a single straight line as seen in Fig. 4 will be obtained.

3 Decays of the used radioactive sources

3.1 β decays

The decay schemes of the used radioactive sources and their respective decay energies are depicted in the subsequent figures. The unstable cesium isotope undergoes a β^- decay:

$$^{137}_{55}\mathrm{Cs} \longrightarrow {}^{137}_{56}\mathrm{Ba} + e^- + \overline{\nu}_e$$

To $94.7\,\%$, the β-decay energy of 514 keV will be released. There exists a competing decay with a probability of $5.3\,\%$, which directly populates the ground state of ^{137}Ba. The released energy in this case amounts to 1176 keV.

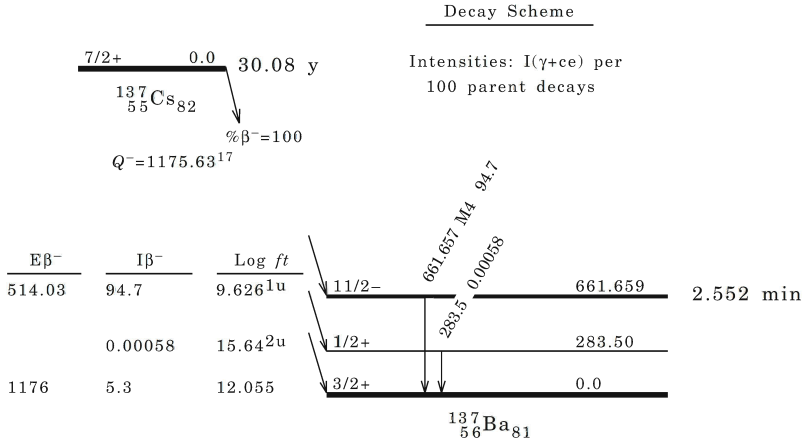


***Figure 5**: Decay scheme of ^{137}Cs to ^{137}Ba, adopted from [3].*

For bismuth ^{207}Bi, a β decay or electron capture to the lead isotope ^{207}Pb is observed:

$$^{207}_{83}\mathrm{Bi} \xrightarrow{\beta^+} {}^{207}_{82}\mathrm{Pb} + e^+ + \nu_e \quad \text{and} \quad {}^{207}_{83}\mathrm{Bi} \xrightarrow{\varepsilon} {}^{207}_{82}\mathrm{Pb} + \nu_e$$

***Table 1**: Possible decay channels of ^{207}Bi*

ε decay		β^+ decay	
intensity	energy [keV]	intensity	energy [keV]
$7,03\,\%$	$57,6$	$0,038\,\%$	$1827,8$
$84\,\%$	$764,1$		
$8,9\,\%$	$1827,8$		

3.2 γ decays

In most cases, after the decay of a parent nucleus, the daughter nucleus will be present in an excited state. For instance, after the β decay of ^{137}Cs, the second excited state on ^{137}Ba is populated with a probability of $94.7\,\%$. It becomes obvious, that a nucleus has many different excited

states. The deexcitation to the ground state proceeds, similar to processes in atomic shells, via the emission of electromagnetic radiation, i.e. γ radiation. The energy of the γ-rays is given by the difference of the involved excitation energies. Every nuclear state represents a defined quantum mechanical state with the fixed quantum numbers spin and parity. The γ-ray must connect these states and ensure angular momentum and parity conservation. For large spin differences and changing parities of the involved nuclear states, large lifetimes occur, as the transition probabilities are small. One example is the second excited state in ^{137}Ba. This state has a rather large half-life of 2.552 min and, thus, is also denoted as metastable or isomeric state.

3.3 Internal conversion (IC)

In chapter 2.1 the electron capture has been introduced, where an electron located in the K has a non-zero probability of presence inside the nucleus. The same holds true for electrons located in the L and M shell, which have a angular momentum of zero (s-wave electrons). Excited nuclei can transfer their energy via Coulomb interaction directly to one of these electrons, which is called internal conversion. The energy of the emitted electrons is given by difference of the nuclear excitation energies minus the electron binding energy:

$$E_{IC} = E_\gamma - E_B$$

Hence, conversion electrons have discrete energies in contrast to the continuous spectrum emitted from β decay. This process represents an alternative process to γ-ray emission, which increases the total transition probability λ_t between the nuclear states:

$$\lambda_t = \lambda_\gamma + \lambda_{IC}\,,$$

where λ_γ and λ_{IC} denote the single transition probabilities. As these processes compete during the transition between two excited states (or ground state), the ratio of these decays is summed

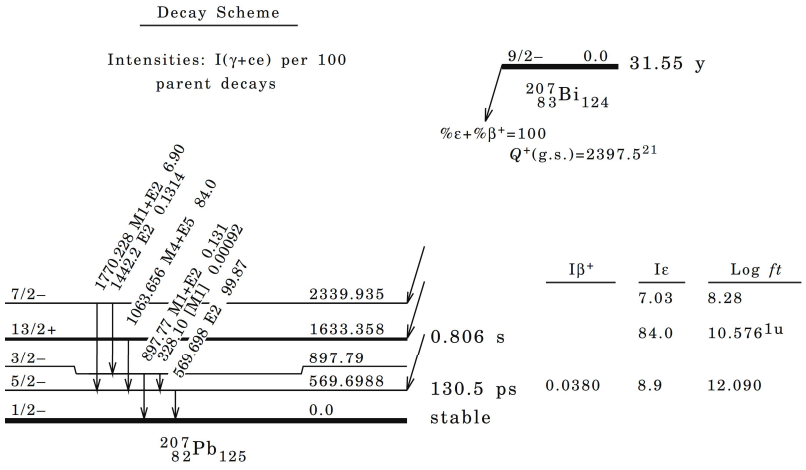


***Figure 6**: Decay scheme of ^{207}Bi to ^{207}Pb, adopted from [7]*

up in one coefficient. The so-called conversion coefficient α is the ratio of the count rate of the emitted γ rays and the count rate of conversion electrons:

$$\alpha = \frac{N_{IC}}{N_\gamma}$$

Transitions with high multipolarities and small energy differences dominantly proceed via internal conversion. The conversion coefficient increases with increasing Z and spin difference, but decreases with rising γ-ray energies. The largest conversion coefficients are found for heavy nuclei with large spin difference and low γ-ray energies. One example is given by the decay of $^{207}_{83}$Bi to $^{207}_{82}$Pb. One can see from the decay scheme, that in $84\,\%$ of all cases, an excited state with $I^\pi = (13/2)^+$ and 1633.36 keV is populated. The possible transitions to the lower-lying state having a spin and parity configuration of $I^\pi = 5/2^-$ must proceed via $M4$ and $E5$ transitions. The energy difference amounts to 1063.66 keV and the conversion coefficient for this transition is given by $\alpha = 0.128$. The isomeric state in ^{137m}Ba also decays via internal conversion. The conversion coefficient in this case is given by $\alpha = 0.1124$. The conversion electrons of both radioactive sources are used for the energy calibration in the present experiment.

4 Experimental setup

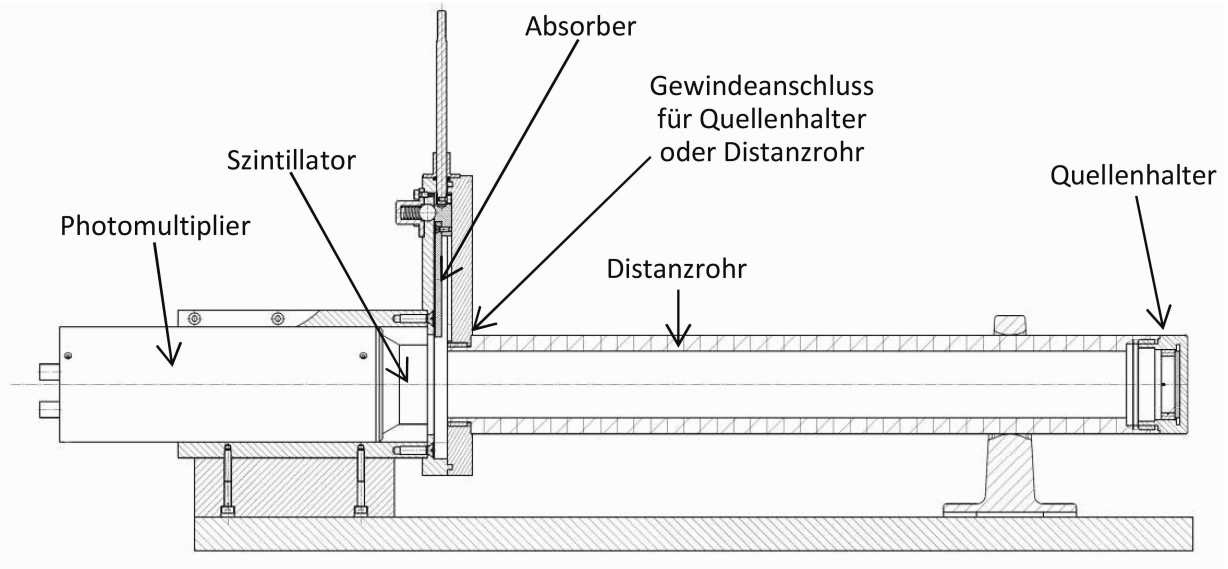


***Figure** 7: Sketch of the experimental setup*

Figure 7 shows a sketch of the experimental setup. The scintillation detector is mounted at a fixed position. Directly in front of the scintillation crystal an absorber is placed, which can be moved in front of the crystal. A thread is provided at the housing, where the sources or the spacer tube can be screwed.
As scintillation material, a p-Terphenyl monocrystal is used for the present experiment. This

crystal is coated with an evaporated layer of aluminum at the entrance window, in order to protect the photomultiplier from environmental light. As the electrons must pass this foil, it was designed to be preferably thin, its thickness amounts to 20 μm and is very touch-sensitive. Thus, do never touch it! The electrons emitted from the sources hit the scintillator and excite its molecules to emit light. The created number of photons is proportional to the energy deposited by the electrons. The scintillator is optically coupled to a photomultiplier (PMT). The created photons are hitting the photo cathode in the PMT and create free electrons via the outer photo effect. By the high voltage applied to the PMT, the electrons are accelerated towards the dynodes, where further free electrons are created. Thus, inside the PMT, the light emitted from the scintillator is amplified. The generated pulse is further processed in the main amplifier (Pulse-Shaping Amplifier). Despite the amplification of the signal, the pulse shape is adjusted in a way that the MCA is able to handle the signal.
The MCA analyzes the single pulses and is read out continuously by a computer and written to a spectrum.

5 Expeirmental procedure

Move the absorber in front of the detector before changing the sources. Otherwise, the photomultiplier can be damaged beyond repair.

The high voltage is only applied by the supervisor.

Handle the radioactive sources with care! Unused sources must be covered! Never touch inside the source retainer! Avoid any contact of the sources with your fingers or sharp objects!

A. Calibration measurements

First, the conversion electrons of ^{207}Bi are measured, in order to relate MCA channels of the peak with a known energy. This measurement will be used, among other things, to perform an energy calibration during the data analysis.

1. Screw the ^{207}Bi source inside the apparatus and measure the spectrum for 15 minutes without absorber
2. Measure again for 15 minutes using the same source, but now with absorber between source and detector. In this way, the electrons cannot be detected. Now the background radiation and γ-rays of the source are measured, which must be subtracted from the first measurement afterwards.

B. Main measurements

3. In a next step, you measure the spectrum of the ^{137}Cs source for 60 minutes without absorber. Remember to move the absorber in front of the detector before changing the source! Similar to the first measurement, the β as well as γ radiation is measured.

4. As one is only interested in the conversion electrons and the continuous electron spectrum, the emitted γ-rays and background radiation must be subtracted as well. Therefore, measure the γ-ray spectrum of the ^{137}Cs source with absorber

C. Influence of source-to-detector distance

5. During the last measurement, the β spectrum of the ^{137}Cs source is measured at a large distance for 15 minutes. Before unmounting the source and mounting the spacer tube, move the absorber in front of the detector in any case!

6. As the detector geometry was changed, a second measurement with absorber must be performed in order to subtract undesired γ-rays from the measured spectrum. Measure for 15 minutes with absorber.

6 Data analysis

Which differences appear for the measured β spectrum compared to the theoretical one taking into account the full width at half maximum? Which mathematical method could be applied to account for the finite resolution of the detector and why are useful results obtained without doing so?
For the Kurie plot, there is an energy and momentum representation. How do they look like and how can they be converted into each other? Which one is the preferred choice in the present case?

1. Calculate and plot the Kurie representation of the ^{137}Cs spectrum. Plot 25 data points at least. Add at three freely distributed point the respective statistical error according to Gaussian error propagation.
   Two competing transitions exist. How can these transitions be separated? Determine the transition energies of both transitions. Discuss possible systematic uncertainties of this measurement.

2. Extrapolate the Kurie plot of the first transition to low and high β energies. From this, calculate the intensities in the respective energy region. By calculating the count rate using the Kurie plot of the first transition, draw several points of the energy and momentum spectrum. What is the difference between them, especially at zero energy and momentum?

3. The γ-ray transition in ^{137}Ba is partly converted. Determine the conversion coefficient α. N_γ can be determined from the count rate of the low-energetic β decay N_{β_1} and the count rate of the conversion electron peak N_e.

4. The conversion electrons are partly backscattered and deposit only a part of their energy in the crystal and are, thus, counted also in N_{β_1}. By comparing your result with the one from literature, $\alpha = 11$ % determine the fraction of backscattered conversion electrons.

5. Determine the absolute and relative resolution of the detector by using the full width at half maximum of the conversion electron peak.
6. Determine the total efficiency of the scintillator for γ of ^{137}Ba assuming that the detection efficiency for β radiation equals one.
7. Calculate the location of the Compton edge and compare this result with the energy at half the height of your measured Compton edge according to your energy calibration. Using the found deviations, discuss the differences in the interaction of charged particles and γ-rays with matter.
8. Calculate the recoil energy of the barium nucleus, when the electron is emitted with the maximal energy of the low-energetic β decay. The momentum of the β particle must be considered as relativistic. Why should the maximal energy of the continuum be used?

A Fermi function

For the Kurie plot you need the values of the Fermi function for each energy. Fit a function of the form

$$F = A_0 \cdot E^{A_1} + A_2$$

to the data of the following table in order to extrapolate to the required energies.

Table 2: *Fermi function F for $Z = 56$. from [1]*

$p_e\,(m_0c^2)$	E [keV]	F for $Z = 56$	$p_e\,(m_0c^2)$	E [keV]	F for $Z = 56$
0.1	2.548639	76.296	4.0	1595.904	5.9808
0.2	10.11977	38.534	4.5	1844.590	5.8091
0.3	22.49962	26.106	5.0	2094.595	5.6615
0.4	39.36376	20.011	5.5	2345.572	5.5318
0.5	60.31524	16.451	6.0	2597.286	5.4159
0.6	84.92310	14.158	6.5	2849.572	5.3111
0.7	112.7548	12.582	7.0	3102.309	5.2151
0.8	143.3990	11.446	7.5	3355.409	5.1266
0.9	176.4798	10.596	8.0	3608.806	5.0443
1.0	211.6627	9.9408	9.0	4116.293	4.8952
1.2	287.2069	9.0025	10	4624.477	4.7623
1.4	368.1569	8.3663	11	5133.169	4.6424
1.6	453.1519	7.9067	12	5642.243	4.5327
1.8	541.2123	7.5576	13	6151.612	4.4317
2.0	631.6294	7.2818	14	6661.213	4.3379
2.2	723.8858	7.0569	16	7680.937	4.1681
2.4	817.5983	6.8687	18	8701.165	4.0173
2.6	912.4794	6.7077	20	9721.746	3.8814
2.8	1008.310	6.5676	25	12274.19	3.591
3.0	1104.922	6.4439	30	14827.48	3.3516
3.2	1202.182	6.3332	35	17381.26	3.1489
3.4	1299.986	6.2333	40	19935.34	2.974
3.6	1398.251	6.1421	45	22489.63	2.8213
3.8	1496.908	6.0583	50	25044.06	2.6865

B Binding energies

***Table 3**: Electron binding energies, adopted from [10]*

nucleus	K shell [keV]	L_1 shell [keV]	L_2 shell [keV]	L_3 shell [keV]
^{137}Ba	37.440	5.990	5.623	5.247
^{207}Pb	88.005	15.861	15.199	13.035

C Safety instructions

Operating instructions for electric powered equipment in the rooms for the practical course

Danger for people

Burns or death by high electric currents

Safety measures:

Pay attention that cables and plugs are not damaged and use them only in the way they are designed for.
In case of damage, or if you have the suspicion that they are damaged inform immediately your supervisor, do not try to repair anything yourself.
Use at maximum one extension cord and only for low powered equipment.
For equipment with large power consumption only wall outlets should be used.

In case of emergency:

Pull the mains plug.
In case of fire: Switch of all electrical equipment as far as possible.

First aid:

People who can give first aid are Görgen, Rolke, Rudolph, Thiel
In case of shock call immediately an emergency physician Tel. **01-112** (from any telephone in the institute, or mobile **112**)
Hospital for accidents: evangelisches Krankenhaus Weyertal.
In case of all accidents also the managing director of the institute has to be informed.
In case of a working inability of 3 or more days an accident report form available from the secretary has to be filled.
The first aid box can be found in the inner stairwell.

13/11/2014
Blazhev

Operating instructions for high voltage equipment in the rooms for the practical course

Danger for people

Instantaneous death by ventricular fibrillation

Safety measures:

Pay attention that cables and plugs are not damaged and use them only in the way they are designed for.
In case of damage, or if you have the suspicion that they are damaged inform immediately your supervisor, do not try to repair anything yourself.
Switch on the high tension only after the cables have been connected and switch it of before disconnecting.

In case of emergency:

Switch of the high tension
In case of fire: Switch of all electrical equipment as far as possible

First aid:

People who can give first aid are Görgen, Rolke, Rudolph, Thiel
In case of shock call immediately an emergency physician Tel. **01-112** (from any telephone in the institute, or mobile **112**)
Hospital for accidents: evangelisches Krankenhaus Weyertal.
In case of all accidents also the managing director of the institute has to be informed.
In case of a working inability of 3 or more days an accident report form available from the secretary has to be filled.
The first aid box can be found in the inner stairwell.

13/11/2014
Blazhev

Universität zu Köln	**Operating instructions**	**Nr.:** **Date:** 13.11.2014 Signature: A. Blazhev

for the rooms of the practical course / institute for nuclear physics

IDENTIFICATION OF SUBSTANCE

Lead bricks

Lead bricks packed in plastic foil can be touched without precautions.
They are very heavy, **put them only in places where they can not drop on your feet!**
If the foil is damaged please pay attention to the following instructions:

DANGER FOR PEOPLE AND ENVIRONMENT

Danger

May cause harm to the unborn child.

May cause damage to organs through prolonged or repeated exposure.

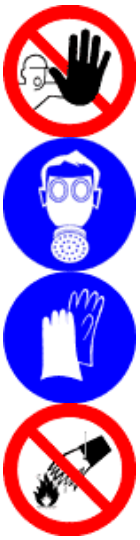
Very toxic to aquatic life with long lasting effects

Warning

Do not breathe dust/fumes/gas /mist /vapours/spray

Avoid release to the environment

SAFETY MEASURES AND RULES



Do not touch any lead brick with a damaged protective foil. If the foil is damaged or if you suspect that it is damaged please inform immediately your supervisor

Breathing equipment: In case of fire toxic metal oxide smoke can be released. Wear self contained breathing apparatus.

Protective equipment: If the protective foil is damaged, lead brick must be touched only with protective gloves**.**

IN CASE OF ACCIDENT	**Fire brigade 01-112 from any phone, mobil 112**

Leave the contaminated area and inform your supervisor. If lead dust has to be removed wear always safety glasses, protective gloves and in case of large quantities a breathing apparatus.
Fire extinguishing measures have to be taken according to the surrounding materials.
In case of a fire dangerous fumes are generated. Please take actions according to the emergency action plan. Call the fire brigade. Lead must not get in the sewage system.

FIRST AID	**emergency physician 01-112, mobil 112**

After eye contact: Rinse opened eye for several minutes under running water. Then consult doctor.
After skin contact: Instantly wash with water and soap and rinse thoroughly.
After swallowing: Seek immediate medical advice.
After inhalation: Supply fresh air. If required provide artificial respiration. Keep patient warm. Consult doctor if symptoms persist.

First aid can provide: **Görgen, Rolke, Rudolph, Thiel**

DISPOSAL

Do not put lead in the sewage or the dust bin. Disposal has to be made via Dr. Blazhev or Bereich 02.2

Radiation protection directive for the handling of radioactive sources in the practical courses of the Institute of Nuclear Physics of the University of Cologne.

Issued 13/11/2014

1. Admission restrictions

Persons under the age of 18 years are not allowed to work in the practical course.

Pregnant women must not work with radioactive sources or in rooms in which radioactive sources are located.

Only students who have filled the registrations sheet and participated in the radiation protection instructions are allowed to carry out experiments with radioactive sources in the rooms of the practical course under the instruction of a supervisor. Visitors must not enter the rooms of the practical course when radioactive sources are located there.

2. Handling of radioactive sources

The radioactive sources are put in the experimental setup or in the lead shielding nearby by a radiation protection officer or an instructed person before the beginning of the practical course. These people document the issue in the list which is placed in the storage room (see appendix B). If radioactive sources have to be transported to other Physics institutes of the University of Cologne a list according to appendix A has to be attached to the transporting container.

When the practical course is finished the same people bring the radioactive sources back to the storage room.

A sign „Überwachungsbereich, Zutritt für Unbefugte verboten“ which means „monitored in-plant area, admission only for authorized personnel” has to be attached to the door of a room of the practical course when radioactive sources are inside.

It is not allowed to remove radioactive sources from the rooms of the practical course without contacting the radiation protection officer before.

During the practical course the radioactive sources must only be located at the place necessary for the measurements or behind the lead shielding nearby the experimental setup.

If you leave the rooms of the practical course make certain that doors are locked and windows are closed, even if you only leave for a short time.

Alpha-Sources are built in the experimental setup and students are not allowed to take them out.

Beta-Sources must only be handled by protective gloves or tweezers.

3. What to do in case of emergency

Any damages or suspected damages of radioactive sources must immediately be reported to the supervisor or the radiation protection officer. It is not allowed to continue work with such a source. Contaminated areas should be cordoned off immediately.

In case of fire, explosion or other catastrophic events besides the managing director and the janitor a radiation protection officer must be called in.

4. Radiation protection officers

Radiation protection officers for radioactive sources in the Institute for Nuclear Physics of the University of Cologne are:

Name	Heinze	Fransen	Dewald
Responsibity	Practical course	Experimental halls, work with radioactive sources, except of the practical course	Work in other institutes, Transport of radioactive sources, accelerator

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