

Coulomb excitation of neutron-deficient polonium isotopes studied at ISOLDE

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Summary

The polonium isotopes represent an interesting region of the nuclear chart having only two protons outside the $Z = 82$ closed shell. These isotopes have already been extensively studied theoretically and experimentally. The heavier isotopes ($A > 200$) seem to follow a "regular seniority-type regime" while for the lighter isotopes ($A < 200$) a more collective behavior is observed. Many questions remain regarding the transition between these two regimes and the configuration mixing between quantum states. Experiments in the lighter polonium isotopes point to the presence of shape coexistence, however the phenomenon is not fully understood. A Coulomb excitation study of the polonium isotopes whereby the dynamic properties are investigated can provide helpful insights in understanding the shape coexistence phenomena. In this thesis ^{202}Po was studied via Coulomb excitation. The ^{202}Po isotope was part of an experimental campaign in which the $^{196,198,200,206}\text{Po}$ isotopes were studied as well via Coulomb excitation.

In a Coulomb excitation event, a beam of nuclei (projectile) is inelastically scattered on target nuclei. After scattering, one or both of the nuclei are left in an excited state due to the exchange of virtual photons of the electromagnetic interaction. The cross section for Coulomb excitation depends in first order on the reduced transition probability $B(E2, I_i \rightarrow I_f)$ and in second order on the quadrupole moment of the populated state and multistep excitations. The $B(E2, I_i \rightarrow I_f)$ value is a measure of the collectivity of the nucleus and the quadrupole moment indicates how much the nucleus deviates from spherical symmetry. These two observables can be determined by Coulomb excitation and thus this technique lends itself perfectly for studying the polonium isotopes.

The experiment studying the $^{202,206}\text{Po}$ isotopes was part of an experimental campaign studying the Coulomb excitation of the neutron-deficient polonium isotopes. At REX-ISOLDE a beam of polonium isotopes was produced and accelerated to 2.85 MeV/u. This beam impinged on the target (^{104}Pd or ^{94}Mo) in the collision chamber. The scattered particles were detected by a position-sensitive double-sided silicon-strip detector (DSSSD). Emitted γ rays originating from the deexcitation of the nuclei were detected by the Mini-ball gamma spectrometer. The detector is also position sensitive. The γ rays are emitted in flight and thus the detected γ -ray energy is Doppler broadened and shifted. In order to perform a proper correction for this effect, position sensitivity of the detectors is needed. Both these detectors need to be calibrated and an absolute efficiency curve for detecting the γ rays was determined using decay data from a ^{133}Ba and ^{152}Eu source.

The first part of the analysis consists of selecting the interesting events. Normally coincidence between two detected scattered particles and a detected gamma ray is employed. This procedure was rendered impossible to use due to problems with the downscaling of the detected events. Therefore a milder constraint had to be used: coincidence between a detected target nuclei and a gamma ray. Once the interesting events were selected the gamma spectrum can be visualized. Two clear photo peaks coming from the deexcitation of target and projectile are present as well as a large amount of X rays. These X rays can originate from two different processes: heavy-ion induced K vacancies due to collisions and conversion electrons. The estimated and observed amount of X rays were then compared. A large discrepancy between estimation and experiment was observed and the origin of these excess X rays was further investigated. A first possible origin was the E0 transition between the second 0^+ state and the ground state. A β^+ /electroncapture-decay study by Bijmens et al. indicated that the E0 transition was highly favored since no transition from the 0_2^+ state to the 2_1^+ state was observed [Bij98]. Strong population of this 0_2^+ state during the Coulomb excitation experiment will give rise to a large amount of X rays. In light of this question the data on ^{206}Po was analyzed. For this isotope the 0_2^+ state is expected to lie very high in energy and thus excess X rays in this isotope must solely come from the atomic effect. A large amount of unpredicted X rays was also present in this isotope so the question still remains as to where these X rays originate from.

The information obtained from the Coulomb excitation experiment was then analyzed using the CLX code. The CLX code uses first order perturbation theory to calculate the cross sections for Coulomb excitation of the populated states. As crucial input the CLX code requires the matrix elements that connect the populated states. Using the known matrix elements of the target the polonium beam flux can be determined. The predicted amount of polonium deexcitation counts can then be compared to the observed amount. The matrix element connecting the 2^+ to the 0^+ state, and thus the cross section, was then varied such that the prediction and observation agreed with one another. A $B(E2, 2^+ \rightarrow 0^+)$ value of 28 (6) W.u. was extracted. An attempt was also made for extracting the diagonal matrix element, related to the quadrupole moment of the populated state, but since only a limited angular range of the DSSSD could be used no conclusion could be drawn. The $B(E2, 2^+ \rightarrow 0^+)$ value was then compared to values predicted from theory and experimentally known values for other polonium isotopes.

In conclusion, a more detailed analysis of the X rays should be performed in order to understand where the large amount of excess X rays originate from. Once the origin is known a more complete analysis can be performed using a more suitable programme (e.g. GOSIA) and the transitional and (possibly) the diagonal matrix element can be determined more accurately. These results can then be added to the result from the other polonium isotopes investigated during the same campaign to gain a more complete understanding of the transition from "regular seniority-type regime" to collective behavior in the polonium isotopes.

Samenvatting

Met twee protonen buiten de gesloten $Z = 82$ schil bevinden de polonium isotopen zich in een interessant gebied van de kernkaart. Deze isotopen werden dan ook al veelvuldig onderzocht, zowel theoretisch als experimenteel. De zwaardere isotopen ($A > 200$) volgen een "algemeen senioriteitsregime" terwijl de lichtere isotopen ($A < 200$) meer collectief gedrag vertonen. Experimenteel bewijs is geleverd voor het bestaan van vormcoëxistentie in de lichtere isotopen. Voorlopig is het fenomeen van vormcoëxistentie nog niet goed begrepen. De studie van de isotopen rond de transitie van senioriteitsregime naar collectief gedrag kan hulp bieden bij het bestuderen en het begrijpen van vormcoëxistentie in kernen. Vooral de menging van verschillende kwantumtoestanden in de polonium isotopen is niet goed begrepen. ^{202}Po werd bestudeerd in deze thesis via Coulomb excitatie om meer inzicht te verschaffen over dit fenomeen. ^{202}Po was deel van een experimentele campagne waarbij een reeks van polonium isotopen opgemeten werden.

Tijdens een Coulomb excitatie experiment wordt een bundel van projectiel kernen op een doelwit geschoten. Hierbij zullen beide kernen verstrooid worden. Na de verstrooiing kan projectiel en/of doelwit zich in een geëxciteerde toestand bevinden door de uitwisseling van virtuele fotonen van de elektromagnetische interactie. De botsingsdoorsnede voor Coulomb excitatie hangt in eerste orde af van de gereduceerde overgangswaarschijnlijkheid $B(E2, I_i \rightarrow I_f)$ en in tweede orde van het quadrupool moment van de gepopuleerde toestand en verdere excitaties. De $B(E2, I_i \rightarrow I_f)$ waarde is een maat voor de collectiviteit van de kern en het quadrupool moment is een maat voor hoe sterk de kern afwijkt van sferische symmetrie. Deze twee observabelen kunnen bepaald worden via Coulomb excitatie en daarom werd deze techniek gebruikt om ^{202}Po te bestuderen.

Het experiment waarbij $^{202,206}\text{Po}$ werden bestudeerd, maakten deel uit van de experimentele campagne om de polonium isotopen te bestuderen. In REX-ISOLDE werd een bundel van polonium isotopen geproduceerd en naversneld tot een energie van 2.85 MeV/u. Deze bundel was gericht op een doelwit, bestaande uit ^{104}Pd of ^{94}Mo atomen, in de botsingskamer. De verstrooide deeltjes werden gedetecteerd door een positiegevoelige dubbelzijdige silicium strip detector. De gammastralen komende van de deëxcitatie van de kernen werden gedetecteerd met de Miniball gamma spectrometer, eveneens positiegevoelig. Aangezien de kernen vervallen voordat ze zijn gestopt in de detector zal de energie van de gedetecteerde gammastralen Doppler verschoven zijn. Om te kunnen corrigeren voor deze verschuiving is deze positiegevoeligheid van beide detectoren vereist. Beide detectoren

werden gecalibreerd en een absolute efficiëntiecurve voor het detecteren van de gammas-tralen werd bepaald gebruik makende van de vervaldata van een ^{133}Ba en ^{152}Eu bron.

In het eerste deel van de data analyse moet een selectie worden gemaakt van de interessante gebeurtenissen. In normale omstandigheden worden deze gebeurtenissen geselecteerd door middel van voorwaarden waaraan voldaan moeten worden: twee verstrooide kernen en de bijhorende gammastraal moeten in coïncidentie met elkaar zijn. Ten gevolge van een probleem met de "*downscalers*" kon deze procedure niet degelijk worden toegepast. Daarom werd geopteerd voor een mildere conditie namelijk: coïncidentie tussen een gedetecteerde doelwit kern en een gammastraal. Eens deze selectie is gedaan kan men beginnen met de analyse van het gammaspectrum. Dit spectrum vertoont twee duidelijke fotopieken komende van het verval van het doelwit en het projectiel. Ook was er een grote hoeveelheid aan K X-stralen aanwezig in het spectrum. Deze X-stralen kunnen komen van twee processen: botsingsgeïnduceerde K-gaten productie en van conversie-elektronen. Een schatting van het aantal X-stralen kan dan gemaakt worden en vergeleken worden met het aantal geobserveerd in het experiment. Een zeer groot verschil tussen deze twee waarden werd opgemerkt en de oorzaak hiervan werd onderzocht. Een eerste mogelijke oorzaak was de E0 transitie van de 0_2^+ naar de grondtoestand. Een β^+ /elektronenvangst experiment van Bijmens et al. had al aangetoond dat deze transitie zeer sterk aanwezig. Het verval van 0_2^+ toestand naar de 2_1^+ toestand was niet aanwezig [Bij98]. Bevolking van deze 0_2^+ toestand zal dan aanleiding geven tot een grote hoeveelheid X-stralen. Om dit vraagstuk op te lossen werd de data van het ^{206}Po experiment ook geanalyseerd aangezien nog geen laagenergetische 0_2^+ toestand werd geobserveerd in dit isotoop.

De informatie verkregen uit het Coulomb excitatie experiment werd geanalyseerd met het computerprogramma CLX. CLX gebruikt eerste orde perturbatietheorie om botsingsdoorsneden te bepalen van de bevolkte toestanden. Als belangrijke input gebruikt CLX de matrix elementen die de verschillende toestanden met elkaar verbinden. Gebruik makende van de informatie over de doelwit kern kan de flux van de bundel bepaald worden. Met CLX kan dan een schatting gemaakt worden van het verwachte aantal tellingen in de fotopiek van het projectiel. Het matrix element dat de 2^+ en 0^+ toestand verbindt, en dus de botsingsdoorsnede, werd dan gevarieerd totdat dit aantal in overeenstemming was met het geobserveerde aantal. De berekende $B(E2, 2^+ \rightarrow 0^+)$ waarde bedroeg 28.0 (6) W.u. Er was ook een poging ondernomen om het diagonaal matrix element te bepalen maar het gebruikte hoektraject van de DSSSD was te beperkt om een degelijk resultaat te bekomen. De $B(E2, 2^+ \rightarrow 0^+)$ waarde werd dan met de andere isotopen vergeleken en met de voorspellingen uit de theorie.

Van zodra de herkomst van de X-stralen volledig is bekend kan een meer vollediger analyse worden uitgevoerd gebruik makend van een meer gepast programma (vb. GOSIA). Het transitioneel en (mogelijk) het diagonaal matrix element kan dan nauwkeuriger bepaald worden. Deze resultaten kunnen dan samengevoegd worden met de resultaten van de andere isotopen bestudeerd in dezelfde campagne en meer inzicht in de overgang van senioriteitsregime naar collectief gedrag in de polonium isotopen kan hieruit resulteren.

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Introduction

This thesis describes the motivation, experimental setup and data analysis of a Coulomb excitation experiment on ^{202}Po that took place at the ISOLDE facility in CERN. The first chapter starts with a general introduction to nuclear structure and a short description about different theoretical models is given. The Coulomb excitation technique and the experimental observables are also described in this chapter. Also, the theoretical and experimental work on the polonium isotopes ($Z = 84$) will be reviewed. This chapter will serve as a motivation to why ^{202}Po was studied.

In the second chapter the experimental setup that was used for the experiment is described. It starts off with a description of how the polonium isotopes were created. For the Coulomb excitation experiment a special detection setup is used since both particles and gamma rays need to be detected. A deeper understanding of this detection setup is given in this chapter. Also the extraction of the absolute efficiency curve for the γ detector array is described in this part together with the calibration method for both detectors. The chapter concludes with a few words about a proper target choice.

The third chapter describes in detail the analysis of the experimental data. First a typical kinematics plot is given and compared to simulation and some words are said about extracting the beam purity. The main part consists of selecting the interesting physical events from the data and extracting the useful information. Problems during the analysis are addressed as well. In the X-ray analysis inconsistencies between theory and experiment are addressed and investigated. The chapter concludes with the CLX analysis. Here the experimentally obtained results are employed to obtain the $B(E2, 2_1^+ \rightarrow 0_1^+)$ value providing information about the nuclear structure of the studied nucleus. The chapter concludes with a short conclusion.

Chapter 1

Motivation

This first chapter serves as a general introduction for the next chapters. An introduction to the nuclear structure and models is given. The kinematics of Coulomb excitation will be addressed and important experimental parameters will be explained. The chapter concludes by giving the motivation for studying the ^{202}Po isotope as well as the usage of the Coulomb excitation technique.

1.1 Nuclear structure

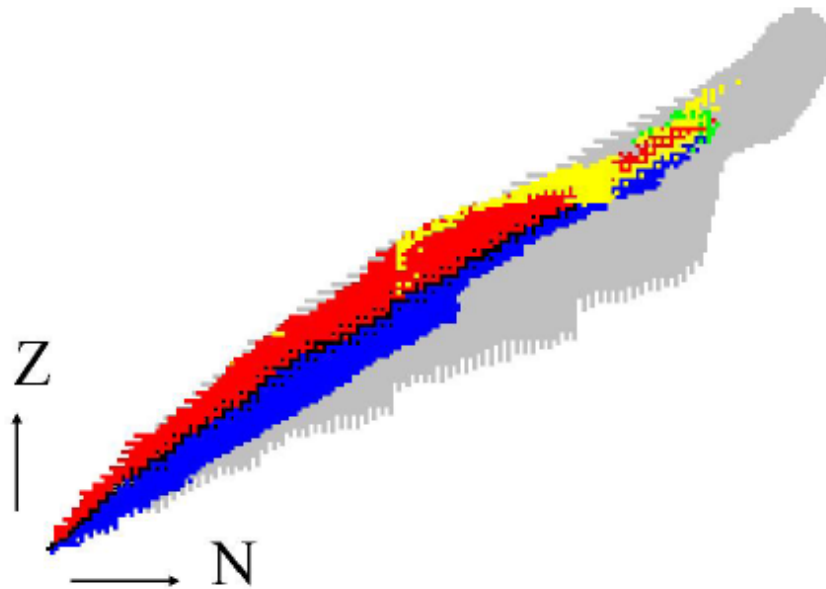


Figure 1.1 – The nuclear chart with the number of neutrons N on the horizontal axis and the number of protons Z on the vertical axis [Mar99]. For explanation of the colors, see text.

An atom consists of a nucleus surrounded by an electron cloud. The nucleus consists of nucleons which can be divided into protons (charge $+1e$) and neutrons (charge zero). For nuclear structure studies the electron cloud is in most cases discarded. The atomic number Z of a nucleus determines the chemical element of the atom. The number of neutrons N in a nucleus of an element can vary. Two nuclei with the same Z but different N are called isotopes of that element. The mass number A of a nucleus is defined as: $A = Z + N$ (total amount of nucleons). To represent a particular nucleus the following notation is used: ${}^A\text{X}$ with X representing the name of the element.

Figure 1.1 shows the nuclear chart. The nuclear chart shows all nuclides that are predicted by theory as a function of their proton number Z and neutron number N . The black squares indicate stable isotopes. The different colors in the chart represent different decay modes: blue = β^- decay, red = β^+ decay/electron capture, yellow = α decay, green = spontaneous fission. The nuclei in grey are predicted theoretically but have not yet been observed experimentally.

To date more than 3600 nuclei are known and 284 of them are stable, the remaining are radioactive. The stability of a nucleus is determined by the two forces at play between the nucleons. The electromagnetic interaction between the protons is repellent and drives the nucleons apart. The strong nuclear force is an attractive force between the nucleons. When there is a sufficient amount of neutrons this force can hold the nucleus together. As can be seen on the chart the ratio N/Z must increase with increasing A to keep the nucleus stable (more neutrons need to be added with increasing Z to overcome the electromagnetic force) while for low A the numbers N and Z are practically equal for stable nuclei. The weak interaction is another important force as it is responsible for the β -decay of nuclei. The stable nuclei, indicated in black in figure , are lying on the so called "beta stability line".

1.2 Nuclear models

To understand the behavior of different nuclei it is essential to describe in detail the nuclear medium which consists of a finite amount of interacting nucleons. This is done by solving the Schrödinger equation for the wave function $\Psi(1, \dots, A)$ with A the number of nucleons. The non-relativistic Hamiltonian is given by:

$$H = \sum_{i=1}^A T_i + \frac{1}{2} \sum_{i,j=1}^A V_{i,j}. \quad (1.1)$$

T_i is the kinetic energy of the nucleon and $V_{i,j}$ the two-body interaction potential [Cas00]. Higher-order terms are neglected in equation 1.1. The exact form of the two-

body interaction is still poorly known and the equation can only be solved analytically for the lightest nuclei.

In order to simplify this complex many-body problem, different theoretical descriptions of the nucleus have been developed. A first simplification is by splitting the Hamiltonian of equation 1.1 in two parts. The first part of the Hamiltonian in equation 1.2 describes the particles as independent particles moving in an average potential while the second part represents the residual interaction between the nucleons. The Hamiltonian can then be written as:

$$H = \left(\sum_{i=1}^A (T_i + U(r_i)) \right) + \left(\frac{1}{2} \sum_{i,j=1}^A V_{i,j} - \sum_{i=1}^A U(r_i) \right) \quad (1.2)$$

where $U(r_i)$ is a central mean-field potential. This mean-field potential can then be chosen accordingly such that the residual interaction can be treated as a perturbation. The Hartree-Fock can be used to determine the mean-field potential. The starting point of the Hartree-Fock calculations is a known nucleon-nucleon interaction potential. The mean-field potential is then determined iteratively with the constraint that the Hartree-Fock energy is minimal. The mean-field approximation can only be used when the long-ranged components of the nucleon-nucleon interaction dominate. However, the short-ranged components of the interaction (e.g. the pairing force) cannot be neglected. To include these short-ranged components different theoretical descriptions can be used. For instance, to include the pairing force, the Hartree-Fock method is combined with the Bardeen-Cooper-Schrieffer method (HF + BCS). In this method the pairing force is incorporated after the calculation of the mean-field potential. Or they can be included in the process of calculating the mean-field as is done in the Hartree-Fock-Bogolyubov theory (HFB) [Hey90].

1.2.1 The Shell model

Experimental evidence has revealed that certain numbers of protons and/or neutrons give rise to exceptionally stable nuclei. These are the so called magic numbers. Near the beta-stability line they are situated at Z or $N = 2, 8, 20, 28, 50, 82, \text{ and } 126$. This stability can be explained by the fact that a certain amount of protons or neutrons lead to the filling of a "shell" of energy levels. These "shells" are separated from each other by large energy gaps. The shell model starts from an harmonic-oscillator potential as a mean-field potential in order to reproduce these "magic" numbers. By using this potential one gets equidistant energy levels. The energy of the different levels is then given by $E_n = \hbar\omega_0(n + \frac{2}{3})$. An important note is that n is not the principal quantum number but simply counts the number of levels with that l value (l is the orbital quantum number). As can be seen from this formula the energy does not depend on l . This potential alone cannot reproduce the magic numbers so the potential has to be modified.

In order to reproduce the magic numbers the spin-orbit interaction needs to be included as well. The spin-orbit interaction is written as: $V_{so} = \vec{l} * \vec{s}$. Using this potential will lead to a further splitting of the energy levels into its $j = l + s$ and $j = l - s$ components (j : total angular momentum). The degeneracy of each level is given by $2j + 1$. By using the spin-orbit interaction the magic numbers can be reproduced. Also an attractive $\vec{l}^2$ term is added to the potential causing additional shifts of the energy levels. Figure 1.2 shows a realistic level diagram.

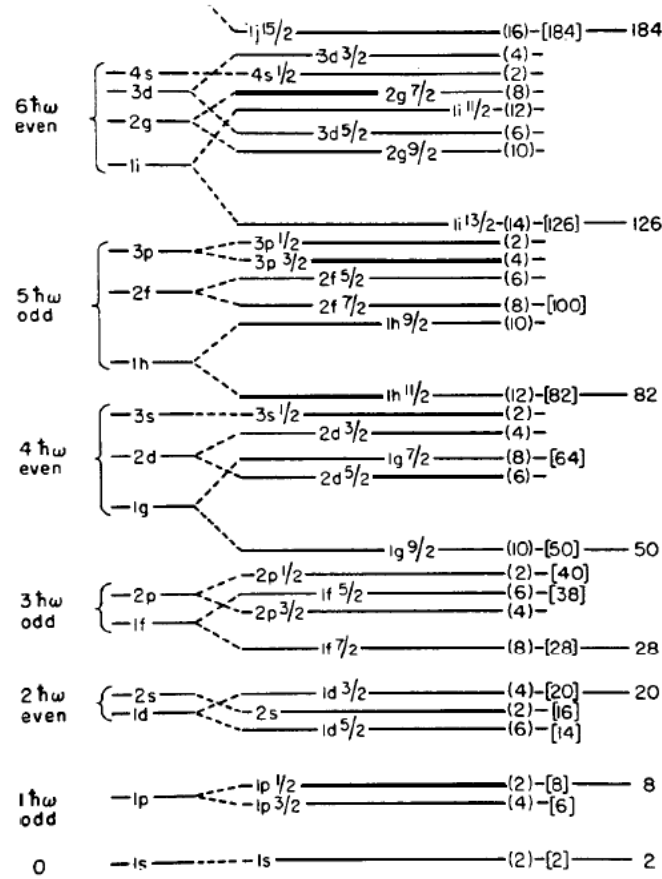


Figure 1.2 – Realistic level diagram. Left on the figure are the levels shown originating from the harmonic-oscillator potential. As can be seen from the figure is that the different oscillator shells consist of different labels. By including the spin-orbit interaction and the $\vec{l}^2$ term, the different labels are split up into two levels and the magic numbers can be reproduced [May63].

When the residual interaction is neglected only doubly-magic nuclei can be described (closed proton and neutron shell). Due to the observed shell structure a nucleus can be considered as an inert core of non-interacting particles and a number of valence nucleons outside this core that interact with each other via the residual interaction. These valence nucleons move in a selected set of shell-model orbits. An appropriate choice of configuration space is thus essential.

Nuclei with only a single valence nucleon are described by the "Independent particle model" [Kra88]. In this model the nucleus is described as having an inert core of non-interacting nucleons with a valence nucleon outside the core. The energy and spin of the ground state are completely determined by this unpaired nucleon. In even-even nuclei the effect of the residual interaction between the nucleons can be limited to a short-ranged pairing force acting on the like valence nucleons. This is observed in the 0^+ ground state in all even-even nuclei.

For nuclei with several valence nucleons the situation is more difficult as there are various ways to make a state with a certain spin and parity. When the number of valence nucleons of both types increases, the proton-neutron interaction increases. This increase can cause the nucleus to deform from its spherical shape and take on a deformed shape. In this case the residual interaction is no longer a small perturbation and the exact diagonalization of the Hamiltonian becomes impossible. Different models can be used then which take into account all the nucleons and not just the valence nucleons.

1.2.2 Mean field

As mentioned in the previous section, the shell model works well for nuclei with few valence nucleons. When the number of valence nucleons increases the nucleus deviates from its sphere-like shape and takes on a deformed shape. In this case the radius of the nucleus can be parameterized in terms of a multipole expansion [Cas00]:

$$R(\theta, \phi) = R_{av} \left(1 + \sum_{\lambda \geq 1} \sum_{\mu = -\lambda}^{\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta, \phi) \right) \quad (1.3)$$

R_{av} is the average nuclear radius in the equilibrium state, $\alpha_{\lambda\mu}$ are the expansion coefficients and $Y_{\lambda\mu}$ are the spherical harmonics. A nucleus can then be excited with angular momentum λ , for example $\lambda = 2$ is the quadrupole deformation. For quadrupole deformations $\alpha_{\lambda\mu}$ can be written as:

$$\begin{aligned} \alpha_{20} &= \beta \cos(\gamma) \\ \alpha_{22} &= \beta \sin(\gamma) / \sqrt{2} \\ \alpha_{2-2} &= \beta \sin(\gamma) / \sqrt{2} \end{aligned}$$

with β as the quadrupole deformation parameter and γ is equal to 0° for prolate deformation and equal to -60° for oblate deformation [Cas00]. A large value of β corresponds to a large deformation and vice versa. Depending on the sign of β the nucleus takes on a distinct shape, see figure 1.3.

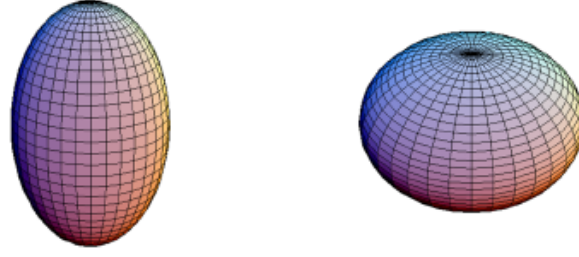


Figure 1.3 – Left: prolate shape ($\beta > 0$), Right: oblate shape ($\beta < 0$) [Kes10].

This deformation can be described in two ways. The first one is the Nilsson model. In this model the nucleons move as independent particles in a deformed (non-spherical) potential. In the spherical case, the energy levels of each single particle with total angular momentum j are $(2j + 1)$ -fold degenerate. If the potential has a deformed shape the interaction energy of the valence nucleons with the core will depend on the relative orientation of the orbit of the valence nucleons with respect to the average shape of the core. The orientation of j with respect to the symmetry axis of the core becomes important. The energy levels will split according to the projection of j on the symmetry axis called Ω ($\Omega = -j \dots j$). Because of the reflection symmetry of the nuclei, the components $-\Omega$ and $+\Omega$ will have the same energy, giving the levels a degeneracy of 2. This splitting depends on the deformation parameter and is typically visualized in a Nilsson graph (figure 1.4) [Kra88].

Another way of dealing with deformed nuclei is via collective approaches. The first collective approach is by seeing the nucleus as vibrating around a spherical equilibrium. The vibrational energy is quantized and expressed in phonons, a quantum of vibrational energy, ($\lambda = 2$: quadrupole vibration, $\lambda = 3$: octupole vibration, $\dots$). By adding phonons of vibrational energy together quasi-degenerate states can be obtained. However theory does not predict the exact energy of the phonon and therefore it has to be regarded as an adjustable parameter. The vibrational model predicts a 0^+ ground state in even-even nuclei. The first excited state is a 2_1^+ state followed by a 0_2^+ , 2_2^+ and a 4_1^+ state at twice the energy of the 2_1^+ state. The three-phonon states will lie at three times the energy of the 2_1^+ state. For a pure vibrational behavior the ratio of $E(4^+)/E(2^+) = 2$ with 4^+ a member of the two-phonon triplet and 2^+ the first excited state. Typically this value ranges between 2 and 2.5 due to the simplicity of the model. However when going higher in energy the vibrational structure gives way due to the occurrence of particle excitations. These particle excitations corresponds to the breaking of a nucleon pair in the ground state and are not part of the collective structure of nuclei [Kra88].

A second collective approach considers the nucleus as rotating around an axis perpendicular to the symmetry axis. The Hamiltonian of the system is given by:

$$H = \frac{\hbar^2}{2\mathfrak{I}} \vec{I}^2 \quad (1.4)$$

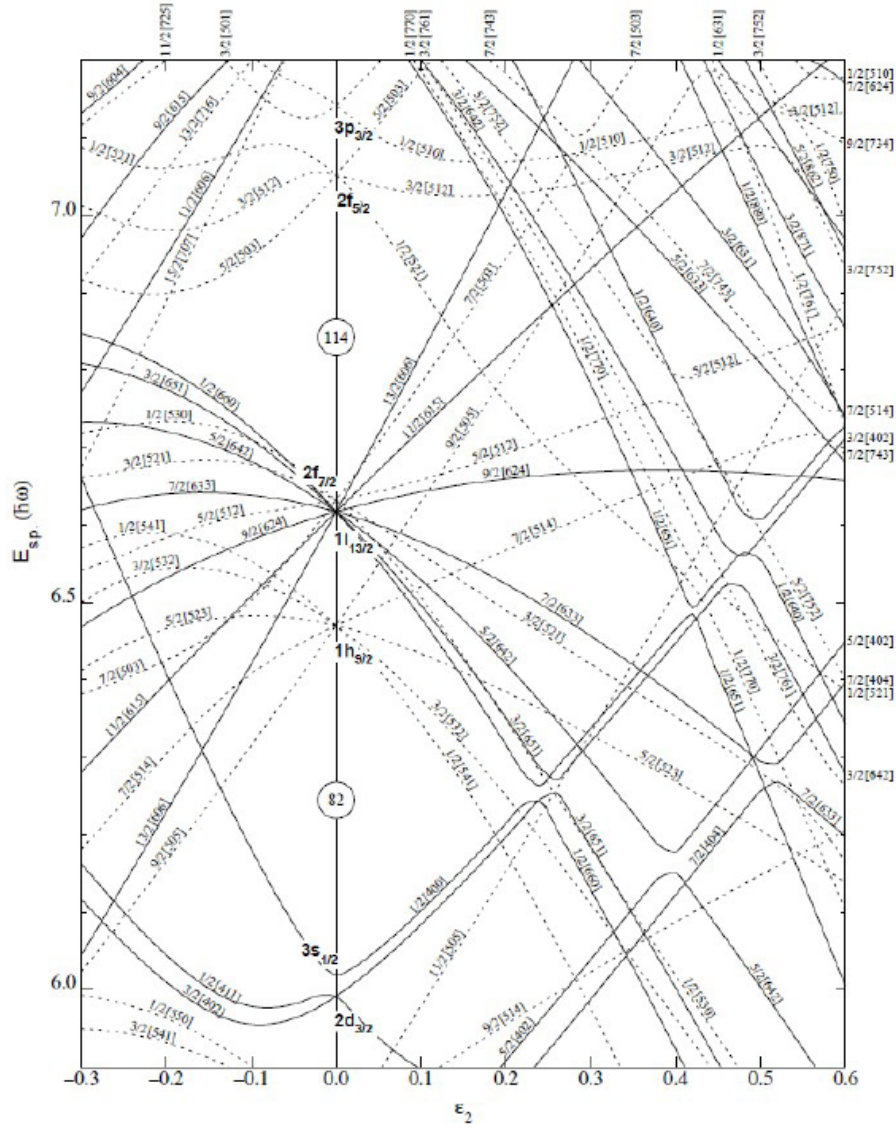


Figure 1.4 – Nilsson graph. The evolution of the single particle energies as a function of the deformation (ϵ_2) for $Z \geq 82$. The parameter ϵ_2 is linked to the quadrupole deformation β by the following relation: $\beta = \sqrt{\frac{\pi}{5}} \cdot \left(\frac{4}{3}\epsilon_2 + \frac{4}{9}\epsilon_2^2 + \dots \right)$ [Fir99]. The notation used for labeling the states is the following: $\Omega[n, n_z, \Lambda]$ with n as the principal quantum number denoting the major shell, n_z the number of nodes of the wave function in the z direction and Λ is the component of the orbital angular momentum along the z axis [Cas00].

$\mathfrak{I}$ is the moment of inertia of the system and $\vec{I}$ the total angular momentum. In this case the total angular momentum $\vec{I}$ of the system is the sum of the angular momentum of the rotating core ($\vec{R}$) and the intrinsic angular momentum of the valence nucleon ($\vec{J}$). K is the projection of the total angular momentum on the symmetry axis and since $\vec{R}$ is perpendicular to the symmetry projection, K is equal to the projection of $\vec{I}$ on the symmetry axis. The total angular momentum can then be written in terms of K and J . The energy of a rotating system is given by [Cas00]:

$$E_{rot} = \frac{\hbar^2}{2\mathfrak{I}} \left(J(J+1) + K(K+1) \right) \quad (1.5)$$

In the case of an even-even nuclei, the projection of the total angular momentum on the symmetry axis is zero, $K = 0$ [Kra88]. For a pure rotational nucleus the ratio $(E(4_1^+))/(E(2_1^+))$ is equal to 3.33.

1.3 Polonium isotopes

The polonium isotopes with $Z = 84$ have 2 protons outside the $Z = 82$ shell. Therefore the polonium isotopes represent an interesting region of the nuclear chart. ^{210}Po with $N = 126$ is a text-book example of a shell-model nucleus having only 2 protons outside the closed shell configuration. For the heavier isotopes ($A > 200$) experimental and theoretical evidence suggest a "regular seniority-type regime" as the energy systematic can be explained by simple two-proton excitations.

In the regular seniority-type regime, the nucleus is described as consisting of paired nucleons together with a small number of unpaired nucleons (ν). For the polonium case this number of unpaired nucleons is equal to two. The energy systematics of the heavier polonium isotopes ($A > 200$) can be explained by considering excitations of these two unpaired protons.

When removing more neutrons from the nucleus, deformed intruder configurations are strongly lowered in energy leading to shape coexistence. It is even suggested that these deformed intruder configurations become the ground-state structure around ^{194}Po . The observed perturbation of the energy systematic for these lighter isotopes are a result of an increased collectivity in these nuclei. A more extreme example of shape coexistence is found in ^{186}Pb where the first two excited states are 0^+ states leading to three types of deformations within a small energy range [And00]. Experimental evidence point out that the transition from a "regular seniority-type regime" to a more collective behavior starts around ^{200}Po . However questions remain about the degree of mixing of the intruder configurations with the spherical ground-state structure and as to how this mixing evolves. Therefore it is important to study the nuclei around this transition point (e.g. ^{202}Po) to gain a better understanding of this matter.

In this section the experimental accomplishments and the predictions of the most successful theoretical approaches for the polonium isotopes will be highlighted.

1.3.1 Experimental information in the polonium isotopes

The level structure and properties along the even-mass polonium isotopic chain have already been extensively studied. In this section, a short description of the information gathered from in-beam γ -ray spectroscopy, decay and laser spectroscopy studies will be

given. In-beam γ -ray spectroscopy has led to the assignment of several level energies, spins and parities in the polonium isotopes. In these studies the polonium isotopes are produced in fusion-evaporation reactions which suffer however from very low cross sections [You95]. The recoil-decay tagging technique is now a new tool used to extract information from in-beam experiments. This technique is especially powerful for neutron-deficient heavy nuclei [Jul01] and [Hel99].

Low-lying states in the polonium isotopes can be fed in alpha decay or beta decay. These studies have been performed at ISOLDE (CERN, Geneva) and at LISOL facility in Louvain-La-Neuve. From the α decay studies information on the low-lying 0_2^+ states has been deduced as well as hindrance factors. [Wau94]. The β^+ /EC decay experiment at the LISOL facility added newly discovered levels to the already observed levels as well as the transitions between them. More importantly, information on the E0 transition between the first excited 0^+ state and the ground state was extracted [Bij98]. Bijmens et al. already concluded in a previous β -decay study that when evolving towards the neutron-deficient polonium isotopes mixing occurs between the normal states and the intruding deformed band. It is this mixing that is responsible for the deviations in energy systematic in the polonium isotopes. However no indication as to the evolution of this mixing was given [Bij95].

Figure 1.5 shows a summary of the energy systematic of the excited states in the even-mass polonium isotopes. In ^{210}Po , which has a closed neutron shell configuration ($N = 126$), a high 2_1^+ state energy and a quasi-degeneracy in energy for the 4_1^+ , 6_1^+ and 8_1^+ are observed. This can be understood in terms of a simple two-proton $\pi 1h_{9/2}$ configuration. When removing two neutrons a drop in energy of the 2_1^+ and 4_1^+ states occur. As more and more neutrons are removed the 2_1^+ state stays rather constant in energy while other yrast states show an increase in energy. At $A = 200$ a transition occurs as the 2_1^+ state now lowers in energy. This drop in energy evolves smoothly down to $A = 188$. For the other yrast states this drop in energy happens rather suddenly and is more pronounced than the drop in energy for the 2_1^+ state. The most notable drop in energy is that of the first excited 0^+ state which seems to evolve towards the ground state between $A = 196$ and $A = 194$ polonium. Thus it appears that ^{200}Po acts as a transitional nucleus marking the end of a "regular seniority-type regime" which is replaced by a down sloping trend for nearly all states [Bas08].

Cocolios et al. studied the ground-state properties of the polonium isotopic chain by means of in-source resonant laser ionization spectroscopy. The experiment was performed at the ISOLDE facility at CERN [Coc10]. The results are shown in figure 1.6. The heavier isotopes follow nicely the trend predicted by the spherical droplet model. However at $N = 114$ a deviation occurs from the prediction of the spherical droplet model. It was also noted that, when moving from heavier to lighter neutron numbers, this deviation occurs at higher neutron number than the other elements with $Z \leq 82$. The deformation parameter for the lighter isotopes was also extracted and was then used to extract the contribution of the deformed wave function to the ground state. The model they used was a two-level

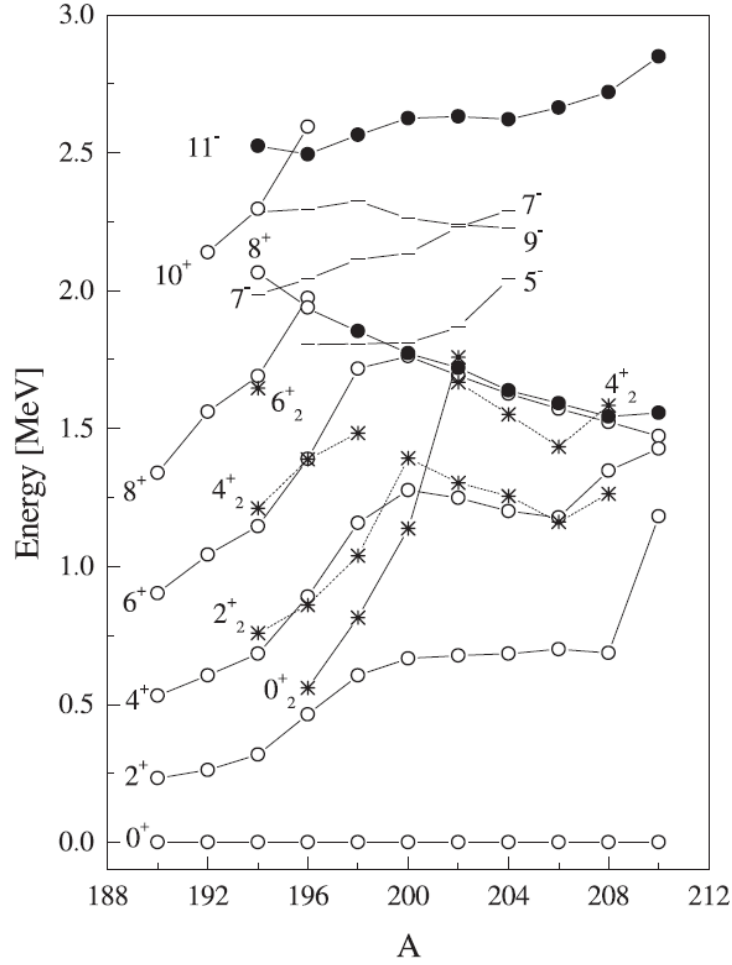


Figure 1.5 – Energy systematics of even-mass polonium isotopes. States with the same spin and parity are connected by a line. The open circles denote the positive-parity yrast levels, the asterisks the non-yrast ones and the bars the negative-parity levels. Isomeric states are denoted by full circles [Jul01].

mixing approach based on α -decay hindrance factors. For $A \leq 194$ it was clear that the contribution of the deformed wave function becomes more prominent as the neutron number decreases [Coc10].

By using the moment of inertia of the nucleus, the degree of deformation can be deduced. These values are in general larger for prolate than for oblate bands. Using lifetime measurements the absolute transition probability can be determined (see 1.4.3). The absolute transition probability can provide information on the collectivity of the nucleus and the degree of mixing of shapes. This has been done for the low-lying states by T. Grahn and collaborators for ^{194}Po and ^{196}Po , [Gra06] and [Gra09]. In their paper it was concluded that the contribution of the oblate component to the ground state lies around 50% (and possibly higher) for ^{194}Po [Gra06].

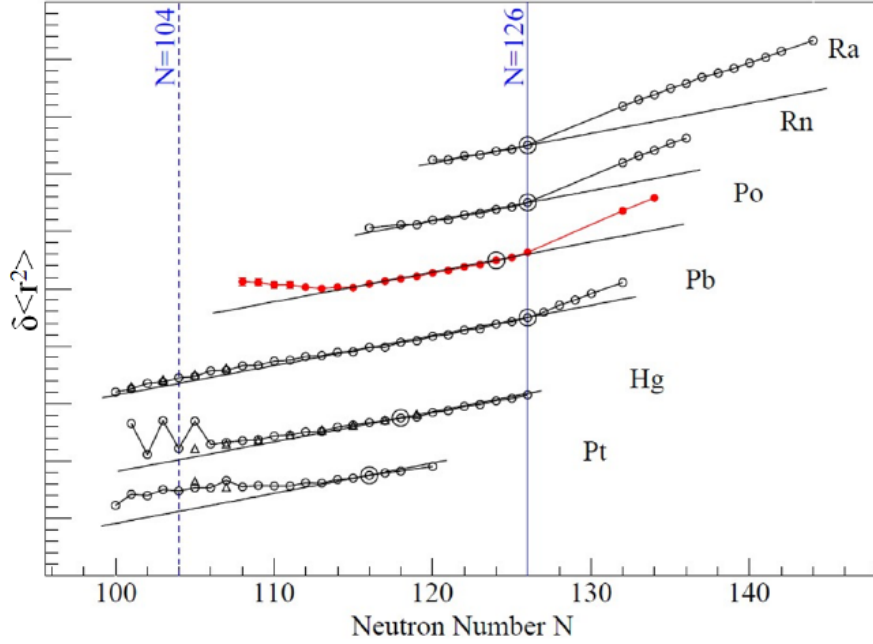


Figure 1.6 – Systematics in the mean-square charged radii $\delta \langle r^2 \rangle$ for the even- Z isotopes of platinum, mercury, lead, polonium, radon and radium. The large circles indicate the reference isotopes for each chain. One large division on the y-axis represents 1 fm^2 . The solid line represents the prediction of the spherical droplet model. The shift between each isotope is arbitrary [Coc10].

1.3.2 Theoretical considerations

The Polonium isotopes have 84 protons and an open neutron shell between $N = 82$ and $N = 126$. This relates to two characteristic features: (i) the two-proton particle degrees of freedom will play an important role in the excitation spectrum; (ii) the collective aspects of the isotopes is the result of the interaction between these two protons and the valence neutrons. The low-energy level scheme of ^{210}Po , which has a closed neutron shell ($N=126$), clearly fulfills the first characteristic and is a textbook example of a "two-particle" nucleus. The first excited state lies high in energy as can be seen in figure 1.5 and most of the excited states (up to 5 MeV) can be explained in terms of simple two-proton excitations in the orbitals above $Z = 82$ [Oro99]. As mentioned before, immediately after leaving the neutron shell closure there is a distinct lowering in energy of the first and second excited 2^+ states and (to a lesser extent) of the 4^+ states. These low-energy excitations are associated with quadrupole vibrations or single-particle motions [Oro99].

An attempt was made at describing the low-energy excitations using the Particle Core Model (PCM). In the PCM the low-energy excitations were explained by considering the coupling of two protons to a vibrating lead core. In figure 1.7 a comparison between the PCM calculations and the experimental values is shown. The PCM calculations are able to reproduce the energies of the yrast states and the 2_2^+ and 4_2^+ non-yrast states. The trend of the 0_2^+ state could not be reproduced by PCM calculations. Although the PCM model was able to give a good description of the low-energy excitations for the heavier

isotopes (up to $A = 200$), for the lighter isotopes the proton-core interaction strength had to be increased very sharply [Ciz97]. Arguments were given against this unphysical sharp rise in the proton-core interaction strength by Ores et al. [Oro99]. Therefore it was concluded that the low-energy excitations in the lighter isotopes were more collective than the PCM calculations indicated [Ciz97]. More information on this can be found in the thesis of Nele Kesteloot [Kes10].

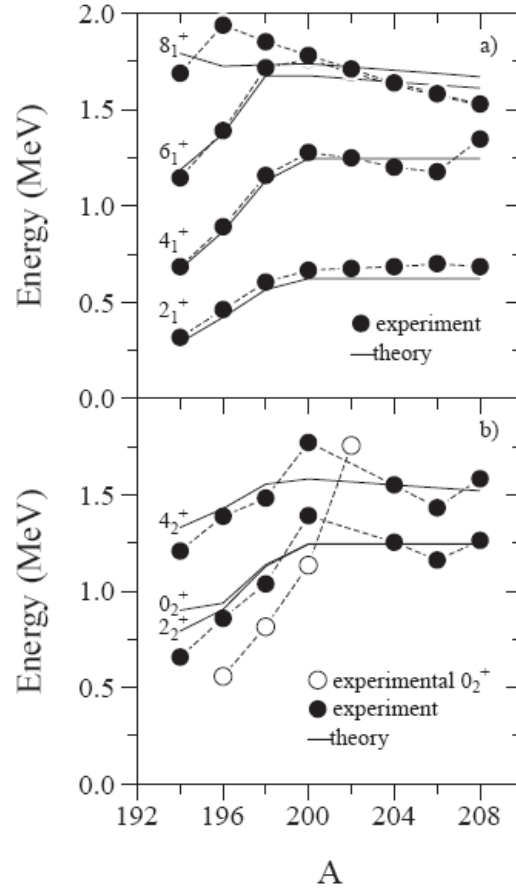


Figure 1.7 – Comparison between experiment and PCM fits for a) the yrast levels and b) the non-yrast levels in $^{194-208}\text{Po}$. The solid lines represent the PCM predictions and the circles represent the experimental values. To be able to reproduce the trend for $A < 200$, the proton-core interaction strength had to be increased [Ciz97].

A recent paper by Heyde and Wood presented a view of shape coexistence in atomic nuclei [Hey11]. The lowering in energy of the low-lying excited states for the lighter isotopes (see figure 1.5) was attributed to a deformed structure that intrudes below the $h_{9/2}$ seniority structure. This intruding structure eventually becomes the ground state between ^{194}Po and ^{196}Po . Also the irregularities in the energies of the 2^+ states indicate that strong mixing must occur around ^{196}Po . However no explanation was given as to how the configuration mixing evolves when going from the heavier to the lighter polonium isotopes [Hey11].

More recently beyond-mean-field calculations have been performed of the even-even polonium isotopes by Yao et al. [Yao13]. Yao et al. started from a set of mean-field wave functions with a constraint on the axial quadrupole moment and using a Skyrme energy density functional. Correlations beyond the mean field, associated with symmetry restorations and fluctuations in the shape degree of freedom, were introduced by projecting mean-field wave functions on angular momentum and particle number. The final wave function for the correlated state was then given by the superposition of the symmetry-restored wave functions as a function of the axial quadrupole moment. The results for the systematics of the low-lying 0^+ states are given in figure 1.8 [Yao13].

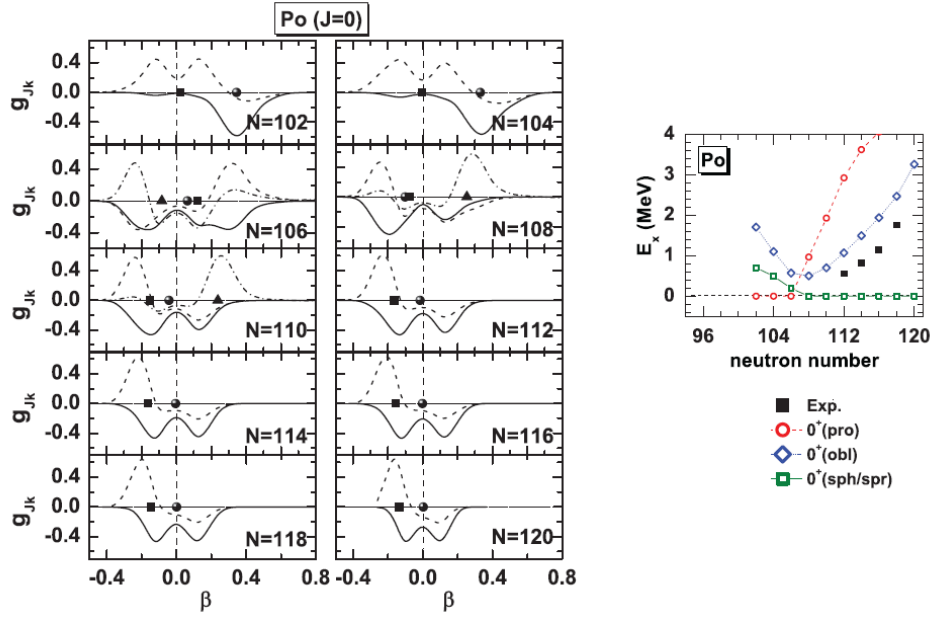


Figure 1.8 – Left: Collective wave functions for the first two (solid and dashed curve) and some selected third (dash-dotted curve) 0^+ states in $^{186-204}\text{Po}$. The mean deformations are indicated with the symbols $\bullet$ (0_1^+), $\blacksquare$ (0_2^+) and $\blacktriangle$ (0_3^+). Right: Systematics of excitation energy of the first three 0^+ states in Po. The available experimental data are plotted for comparison [Yao13].

Their calculations show that for $N = 102$ and 104 , the ground states are dominated by prolate deformations. For the heavier isotopes the ground state showed a larger spreading, an almost equal mixing of prolate and oblate deformation was present. This was interpreted as due to the increased γ softness of their energy surface. For the lightest polonium isotopes the mean deformation for the excited states was small, reflecting the near equal weight of prolate and oblate configurations. The first excited state of the heavier polonium isotopes studied was dominated by oblate components while the second excited state is prolate. The ground state of the polonium isotopes down to $N = 112$ was interpreted as being spherical, while the lighter isotopes possess more deformed ground states. Calculation of the excitation energy of the 0_2^+ state revealed that although the slope of the variation of the energy with N was reproduced, the excitation energy was overestimated (see figure 1.8 right panel). Systematics of the low-lying 2^+ and 4^+ state were investigated as well and compared to experimental values, see figure 1.9 [Yao13].

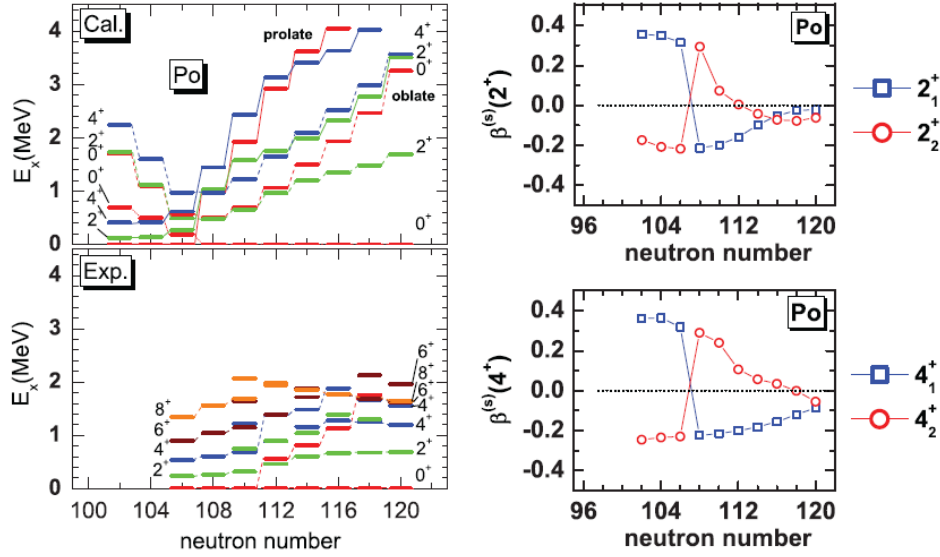


Figure 1.9 – Left: Systematics of calculated (top panel) and experimental (bottom panel) low-lying 0^+ , 2^+ and 4^+ states in the Po isotopes. The experimental data for the lowest 6^+ and 8^+ states are given as well to indicate the evolution of the band structure. Right: Quadrupole deformation β^s of the two lowest $J=2$ (top panel) and $J=4$ (bottom panel) calculated from the corresponding spectroscopic quadrupole moments as function of the neutron number [Yao13].

The calculation shows an overestimation of the excitation energy, close to a factor of two, when compared to the experimental data for the heavy polonium isotopes. The near constant value of the first 2^+ state for the heavy isotopes is not reproduced at all. It was suggested that these isotopes are probably not collective and the inclusion of np - mh excitations for the low-energy intruder states was required for these isotopes. For the isotopes with mass number $N = 106$ -116, the calculated spectra were found to be more realistic and better fitting to the experimental data [Yao13].

From the spectroscopic quadrupole moment, the quadrupole deformation parameters (β^s) were determined and plotted as a function of the neutron number, see right panels figure 1.9. For the heaviest polonium isotopes β^s was very small. This was interpreted as the 2^+ and 4^+ not being based on a deformed state but based on np - mh excitations. Yao et al. reasoned that the too large excitation energies of the 2^+ and 4^+ states might originate from this [Yao13]. Also visible is the distinct crossing between the oblate and prolate configuration at $N = 106$ for the 2^+ and 4^+ states [Yao13]. In figure 1.10 the quadrupole deformation $\beta^t(2_k^+ \rightarrow 0_k^+)$ corresponding to the $B(E2, 2_k^+ \rightarrow 0_k^+)$ are plotted for the transition of the first 2^+ to the ground state and the 0_2^+ . The experimental data is plotted as well in this figure [Yao13].

The experimental $\beta^t(2_1^+ \rightarrow 0_1^+)$ is reproduced quite well by the calculation for the $N = 116$ polonium isotope corresponding to a transition from the oblate 2_1^+ to the spherical ground state. But for $N = 112$ and 110 the transition to the calculated 0_2^+ seems to be

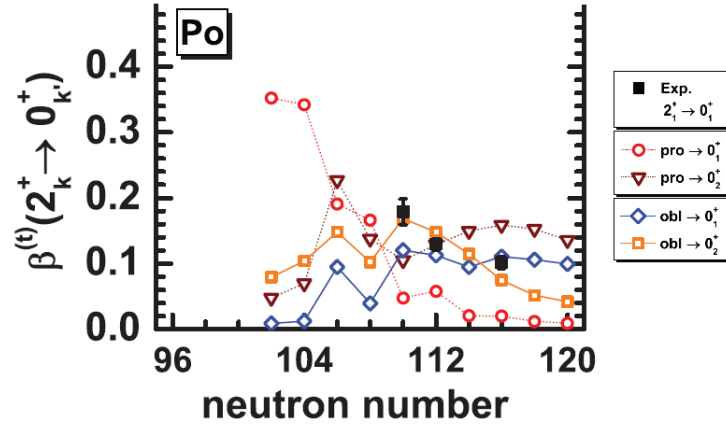


Figure 1.10 – Systematics of the deformations β^t derived from the reduced $E2$ strengths for the transition from the predominant prolate and oblate 2^+ states to the first two 0^+ states as a function of neutron number [Yao13].

in better agreement with the experimental information. This was interpreted as an onset of oblate deformation starting at $N = 112$ which is consistent with observations coming from experimental isotope shifts [Yao13].

In conclusion, the energy systematics of the excited states of the polonium isotopes show an evolution from a "regular seniority-type regime" for the heavier isotopes to a more collective behavior for the lighter isotopes. This increase in collectivity has been attributed to the strong lowering in energy of the intruder states which are responsible for the observed perturbation of the systematic. These intruder structures eventually mix with the ground state structure, even becoming the ground state for the very light isotopes, but the evolution of this mixing remains poorly understood. A detailed study of a series of polonium isotopes that are representative for the transition region should provide new information on the degree of mixing in these isotopes. In the present work the ^{202}Po isotope that lies in the beginning of the transition towards the more collective behavior is discussed.

1.4 Coulomb excitation

The level structure of the even-mass polonium isotopes has been studied thoroughly. Experimental evidence suggests that the heavier isotopes show general seniority-type behavior while in the lighter isotopes shape coexistence dominates. The reduced transition probability $B(E2, 0_1^+ \rightarrow 2_1^+)$ offers a direct measurement of the collectivity and insight in the mixing of different shapes. The technique of safe Coulomb excitation has been used to extract the $B(E2)$ for ^{202}Po . This value will then be compared to previously known $B(E2)$ values of the polonium isotopes and to state-of-the-art mean field calculations. In this section some main features of Coulomb excitation are discussed and the important experimental observables are addressed.

1.4.1 Kinematics

In figure 1.11 a schematic representation of the scattering process is shown. In the scattering process an incoming nucleus, called the projectile, is scattered off a stationary nucleus called the target. In figure 1.11 ^{202}Po is used as a projectile and ^{104}Pd is the target.

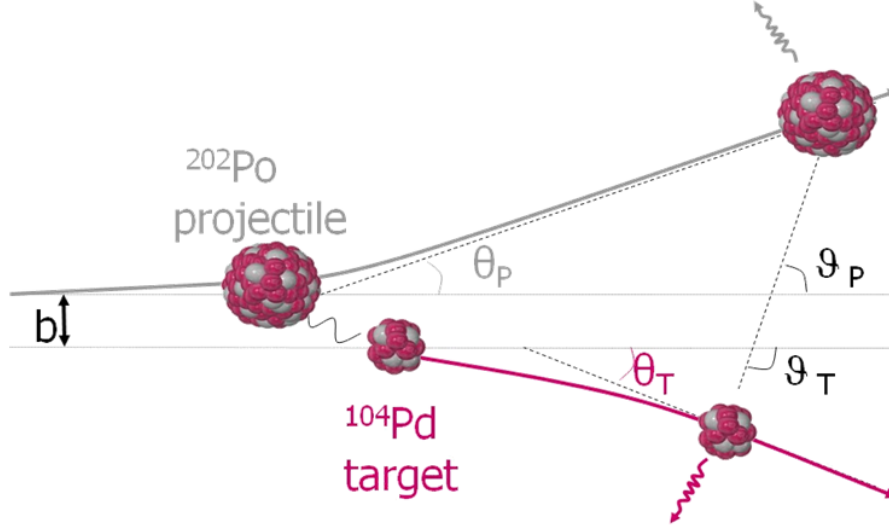


Figure 1.11 – Schematic representation of the Coulomb excitation process. In this figure θ_p en θ_t are the laboratory scattering angles and ϑ_p and ϑ_t are the center-of-mass scattering angles of the projectile and the target respectively [Bre06].

The scattering process of a projectile nucleus $^{A_p}_{Z_p}Y$ on a target nucleus $^{A_t}_{Z_t}X$ is described by the time dependent Schrödinger equation:

$$i\hbar \frac{\partial}{\partial t} |\Psi(t)\rangle = \left(H_o + V(r(\vec{t})) \right) |\Psi(t)\rangle \quad (1.6)$$

where $V(r(\vec{t}))$ is the electromagnetic interaction between the projectile and the target. The electromagnetic interaction can be expanded in terms of electric and magnetic multipoles. The classical Rutherford scattering, or elastic scattering, is described by the monopole-monopole part of the electromagnetic interaction. It is advised to choose one of the colliding nuclei to have a ground-state spin of zero and high-lying first excited state. This will ensure that only one of the nuclei is excited significantly and thus Coulomb excitation can be described by the monopole-multipole interaction [Cli86]. After the inelastic scattering process one or both of the nuclei are left in an excited state. This is achieved through the exchange of the virtual photon of the electromagnetic interaction. Assuming that the trajectory of the nucleus is not affected by the excitation, the differential excitation cross section can then be written as the product of the Rutherford differential cross section and the excitation probability:

$$\frac{d\sigma_n}{d\Omega} = \frac{d\sigma_R}{d\Omega} \times P(i \rightarrow f) = \frac{1}{4}a^2 \sin^{-4}\left(\frac{\vartheta_p}{2}\right) \times P(i \rightarrow f) \quad (1.7)$$

where $\frac{d\sigma_R}{d\Omega}$ is the differential cross section for Rutherford scattering and $P(i \rightarrow f)$ is the probability that a nucleus gets excited from an initial level i to a final level f through the exchange of the virtual photon. The factor a in the Rutherford elastic scattering cross section is given by:

$$a = \frac{Z_p \times Z_t \times e^2}{4 \times \pi \times \varepsilon_o \times E_{CM}} \quad (1.8)$$

with Z_p and Z_t as their respective atomic numbers. E_{CM} is the beam energy in the center-of-mass frame (in MeV) and ϑ_p is the scattering angle of the projectile in the center-of-mass frame. The parameter b , called the distance of closest approach or impact parameter, is the minimal vertical distance between the projectile and target [Ald56]. The distance of closest approach as a function of the "center-of-mass" angle is given by the following formula:

$$b(\vartheta) = a \times \left(1 + \frac{1}{\sin(\vartheta_p/2)}\right) \quad (1.9)$$

with a given by equation 1.8. The relation between the impact parameter and the beam energy can be easily explained. As both the projectile and target nucleus are positively charged they will experience an electromagnetic repulsion when approaching each other. If one wants to decrease the distance of closest approach between the target and projectile, the beam energy needs to be increased. This is due to the rising Coulomb barrier when coming closer to the target [Ald75].

The semi-classical approach of Coulomb excitation is only valid when the excitation process is only due to the electromagnetic interaction. When the distance of closest approach between the target nucleus and projectile nucleus becomes sufficiently small (few fm) nuclear interactions will come into play. Whenever the excitation process is purely due to the electromagnetic interaction it is called "safe" Coulomb excitation. In order to achieve this, the distance of closest approach has to exceed a certain minimal value. This minimal value is calculated using the following formula:

$$b(\vartheta) \geq b_{safe} = R_P + R_T + \Delta. \quad (1.10)$$

R_i is the radius of the nucleus and this can be calculated using: $R_i = 1.25A_i^{1/3}$. Equation 1.10 shows that the safe distance is equal to the sum of the radii of the nuclei, plus an extra value Δ . Typical values for Δ lie around 5 fm, the range of the strong interaction [Cli86].

In order to simplify the calculations the center-of-mass frame will be used. In the center-of-mass frame the projectile and target will be scattered "back to back" and thus there is a simple relationship between the scattering angles of the projectile and target: $\vartheta_p = \pi - \vartheta_t$. The laboratory scattering angles can be transformed into the center-of-mass scattering angles by the following formula:

$$\tan(\theta_p) = \frac{\sin(\vartheta_p)}{\cos(\vartheta_t) + \tau}. \quad (1.11)$$

τ in this formula is given by:

$$\tau = \frac{m_p}{m_t} \sqrt{\frac{E_p}{E_p - \Delta E(1 + m_p/m_t)}} \quad (1.12)$$

where ΔE is the excitation energy of the nucleus due to Coulomb excitation [Ald75].

1.4.2 Cross section of Coulomb excitation

Under most experimental conditions the interaction between the target and the projectile is weak. The probability for excitation during a single encounter is then also small. The probability to excite from a level i to a level f is given by the following formula:

$$P_{if} = |b_{if}|^2 \quad (1.13)$$

Assuming the interaction is weak; the coefficients b_{if} can be calculated in a first order perturbation theory approach:

$$b_{if} = \frac{1}{i\hbar} \int_{-\infty}^{+\infty} \langle f | V(\vec{r}(t)) | i \rangle \exp(i\omega t) dt \quad (1.14)$$

with $\omega = (E_f - E_i)/\hbar$ and $V(\vec{r}(t))$ the interaction energy. The result links then the excitation probability with the $B(E\lambda)$ value [Ald56] (see also next section: Experimental observables):

$$P(i \rightarrow f) = f\left(B(E\lambda, i \rightarrow f), E_p\right) \quad (1.15)$$

Using first-order perturbation theory, the differential cross section for an electric and magnetic transition can be calculated (see [Ald56]):

$$d\sigma_{E\lambda} = \frac{Z_1 e}{\hbar \nu} a^{-2\lambda+2} B(E\lambda, i \rightarrow f) df_{E\lambda}(\vartheta, \xi) \quad (1.16)$$

$$d\sigma_{M\lambda} = \frac{Z_1 e}{\hbar c} a^{-2\lambda+2} B(M\lambda, i \rightarrow f) df_{M\lambda}(\vartheta, \xi) \quad (1.17)$$

where Z_1 is the charge number of the projectile (target) for target (projectile) excitation, $\nu = \sqrt{\frac{2}{m_p}(E_p - \Delta E_n(1 + m_p/m_t))}$, ΔE_n = the excitation energy and $\xi = \frac{\Delta E_n}{\hbar} \frac{a}{v}$ (the adiabaticity parameter). The functions $df_{E\lambda}(\vartheta, \xi)$ and $df_{M\lambda}(\vartheta, \xi)$ contain the familiar $\sin^{-4}$ factor known from the Rutherford cross section as can be seen in equation 1.7. Detailed expressions for these functions can be found in the literature [Ald56]. The total cross section can then be calculated by integrating over all possible scattering angles. In figure 1.12 the calculated cross section for the elastic and inelastic scattering together with the excitation probability as a function of the center-of-mass scattering angle are shown. Figure 1.12 clearly shows the diverging character of the Rutherford scattering at low angles. The Coulomb excitation does not show this diverging character.

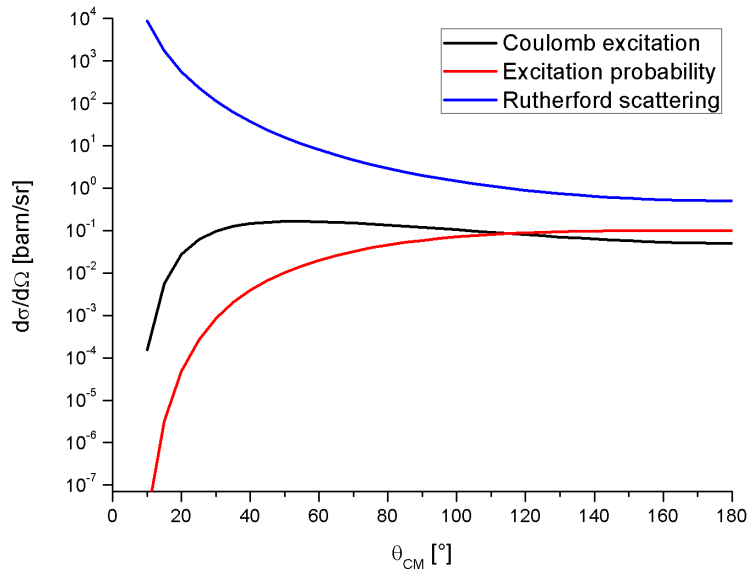


Figure 1.12 – The differential cross section for Rutherford scattering and for Coulomb excitation and the excitation probability $P(i \rightarrow f)$ for ^{202}Po on ^{104}Pd . The cross sections were calculated using the code "CLX". The input values were $E_p = 2.85 \text{ MeV/A}$, $E(2_1^+) = 677 \text{ keV}$ and $B(E2, 0_1^+ \rightarrow 2_1^+) = 0.993 \text{ e}^2 b^2$.

Up to now, only first-order effects of Coulomb excitation were discussed. But during the interaction second- and higher-order effects can come into play as well (especially at high incident energy of the projectile). An example of such a second-order effect is the influence of the quadrupole moment. Figure 1.13 shows two possible higher-order effects [vdW06].

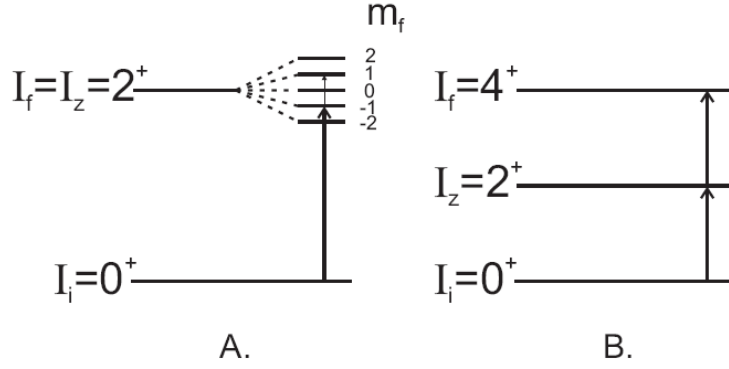


Figure 1.13 – Two examples of higher-order effects. A: Effect of the quadrupole moment. B: 2-step excitation to the final level. [vdW06].

The right of figure 1.13 shows the effect of a double E2 excitation. This leads to a final state that cannot be populated by a single step excitation. The order of magnitude of the cross section for such a double excitation is approximately given by [vdW06]:

$$\sigma_{E2,E2} \sim \sigma_{E2}(I_i \rightarrow I_z) \times \sigma_{E2}(I_z \rightarrow I_f). \quad (1.18)$$

Second to be discussed is the effect of the quadrupole moment. During the interaction between the projectile and the target local magnetic and electric fields are generated. These fields can become large if the incident energy of the projectile is high. Under the influence of these fields the final state will be split up into its magnetic substates. The splitting depends on the magnitude of the electric and magnetic field and on the sign of the quadrupole moment of the final state. If this quadrupole moment is zero for the final state the splitting is zero. The final state after the Coulomb excitation can now be any of these substates. Transitions between different substates can also come into play (this is a special kind of two-step Coulomb excitation). This effect is described by second-order perturbation theory and is called the "reorientation" effect. Each substate represents a different orientation of the nuclear spin of the excited state. The angular distribution of the emitted γ ray and the excitation probability are both influenced by the nuclear spin. For example: the excitation probability for a transition from a 0_1^+ state to a 2_1^+ state is given by:

$$P_{2_1^+} \propto |\langle 2_1^+ \parallel E2 \parallel 0_1^+ \rangle|^2 \times \left(1 + \langle 2_1^+ \parallel E2 \parallel 2_1^+ \rangle \times K(\theta, E_p) \right). \quad (1.19)$$

$K(\theta, E_p)$ is a function which strongly depends on the scattering angle. $\langle 2_1^+ \parallel E2 \parallel 2_1^+ \rangle$ is the reduced matrix element that links the 2_1^+ state to itself via the quadrupole operator [Ald75]. This matrix element is related to the spectroscopic quadrupole moment of the 2_1^+ state:

$$\langle 2_1^+ \parallel E2 \parallel 2_1^+ \rangle = \frac{1}{0.7579} \times Q. \quad (1.20)$$

The influence of this diagonal matrix element on the cross section is only detectable if the absolute value of the term $\langle 2_1^+ \parallel E2 \parallel 2_1^+ \rangle \times K(\theta, E_p)$ is comparable to (or larger than) one. Figure 1.14 illustrates the effect of this second-order effect on the differential cross section for Coulomb excitation. More information and details about Coulomb excitation can be found in the literature [Ald56] and [Ald75].

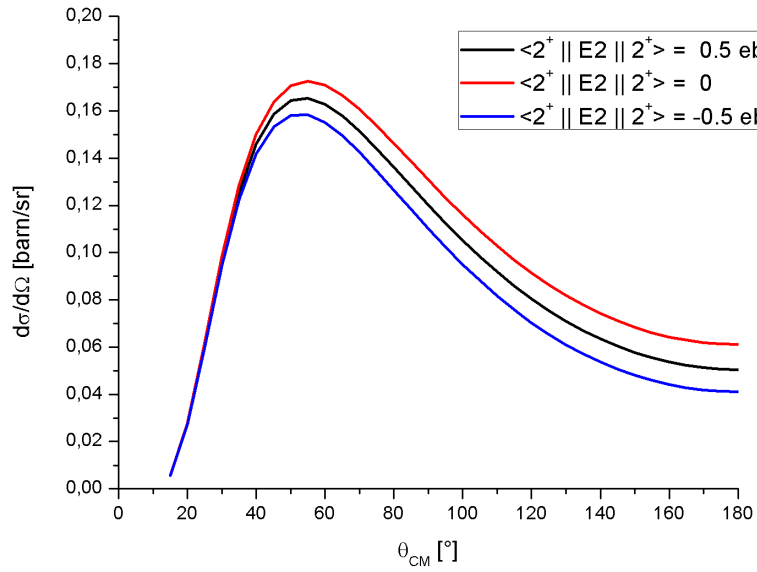


Figure 1.14 – The differential cross section for Coulomb excitation for ^{202}Po on ^{104}Pd for different values of the diagonal matrix element. The calculations were performed using the CLX code. The input values were the same as in figure 1.12 except for the addition of the diagonal matrix element. The values used for the diagonal matrix element are show in the graph.

1.4.3 Experimental observables

This section will describe some observables that can be measured in Coulomb excitation experiments. In general, the electromagnetic transition strength of multipolarity λ is defined as:

$$B(L\lambda, J_i \rightarrow J_f) = \frac{1}{2J_i + 1} \times |\langle \Psi_f \parallel M(L, \lambda) \parallel \Psi_i \rangle|^2 \quad (1.21)$$

where the electromagnetic operator $M(L, \lambda)$ has either an electric ($L=E$) or a magnetic ($L=M$) character and $\langle \Psi_f \parallel M(L, \lambda) \parallel \Psi_i \rangle$ being the reduced matrix element [Ald56]. These matrix elements, which connect different states involved in the γ deexcitations,

contain direct nuclear structure information. The electric quadrupole transition strength for a $0^+ \rightarrow 2^+$ transition is thus defined as:

$$B(E2, 0^+ \rightarrow 2^+) = |\langle \Psi_{2^+} || M(E2) || \Psi_{0^+} \rangle|^2. \quad (1.22)$$

In order to compare B(E2) values of different nuclei a standard for the B(E2) values is defined. The most commonly used standard is the Weisskopf unit (W.u.):

$$1W.u. = 5.94 \times 10^{-6} A^{4/3} e^2 b^2. \quad (1.23)$$

The Weisskopf unit allows a rough estimate of the number of nucleons contributing to the transition. A value close to 1 indicates a single-particle behavior while larger values indicate a collective behavior (typical values 10-50 W.u.). In the single-particle case, the electromagnetic transition is the result of one (or two) particles changing its (their) state. In collective nuclei, the electromagnetic transition is the result of a collective motion involving many nucleons [Hur06]. Careful attention has to be taken for the definition of the Weisskopf unit. The above definition regards the B(E2) value from the 2^+ state to the 0^+ state, also defined as $B(E2 \downarrow)$. Another definition of the Weisskopf unit might consider the 0^+ state as the initial state.

The $B(E2, 0_1^+ \rightarrow 2_1^+)$ value is also related to the lifetime of the 2_1^+ state:

$$\tau_{\gamma, 2_1^+} [ps] = 40.81 \times 10^{13} E_{keV}^{-5} / B(E2, 0_1^+ \rightarrow 2_1^+)_{e^2 b^2} \quad (1.24)$$

This relationship is widely used in experiments. By measuring the lifetime of the excited state the quadrupole transition strength can be determined and vice versa [vdW06].

A last relevant experimental parameter in Coulomb excitation experiments is the electric quadrupole moment (Q). The electric quadrupole moment expresses the deviation from spherical symmetry in the specified direction. Depending on the sign of Q the shape can be either prolate (Q>0), oblate (Q<0) or spherical (Q=0). The spectroscopic quadrupole moment is defined as:

$$Q = \langle I, M = I | \hat{Q} | I, M = I \rangle \quad (1.25)$$

and the quadrupole operator is given by:

$$e\hat{Q} = \int \rho(\vec{r}) r^2 (3 \cos^2(\theta) - 1) d\nu \quad (1.26)$$

[Hur06]. In measurements the spectroscopic quadrupole moment is measured. This differs from the intrinsic quadrupole moment (Q_o) that would be observed in the reference frame in which the nucleus is at rest. The intrinsic quadrupole moment contains the information about the nuclear shape. For a 2_1^+ state in an even-even nucleus there is a direct relationship between the spectroscopic and intrinsic quadrupole moment: $Q = -2Q_o/7$. Thus the spectroscopic and intrinsic quadrupole moment are opposite in sign. In the rotational model, the intrinsic quadrupole moment can be linked with the deformation parameter β :

$$Q_o = \frac{3}{\sqrt{5}\pi} R_{av}^2 Z \beta (1 + 0.16\beta) \quad (1.27)$$

where R_{av} is the average nuclear radius and β is the deformation parameter [Kra88].

1.4.4 Application to experiment

After the inelastic scattering the nuclei will deexcite through the emission of a gamma ray. These gamma rays were detected by the Miniball Germanium detector array (further explanation in section 2.3). Assuming that the state of interest is solely populated by Coulomb excitation and not by decay or feeding paths of other states, the excitation probability can be determined. And as explained before the deexcitation probability can then be linked to the B(E2) value and thus information on the B(E2) value can be extracted. By determining the number of deexcitation counts (e.g. deexcitation of the first excited state to the ground state), the total cross section for Coulomb excitation can be determined by the following equation [Kes10]:

$$N_\gamma^{Po}(2_1^+ \rightarrow 0_1^+) = \varepsilon_{MB,Po} \cdot \sigma_{E2,Po} \cdot \frac{\rho d N_A}{A} \cdot N_{Po} \quad (1.28)$$

where $\varepsilon_{MB,Po}$ is the absolute efficiency of the Miniball detector at the energy of the 2_1^+ state in ^{202}Po , ρd is the target thickness, N_A is Avogadro's number, A is the mass number of the target, N_{Po} is the number of incoming ^{202}Po nuclei and $\sigma_{E2,Po}$ is the total cross section for Coulomb excitation to the 2_1^+ state. The number of incoming polonium nuclei can be determined by the beam flux. However, since the polonium beam is a weak radioactive beam and the beam flux fluctuates, that number cannot be determined accurately. Here lies the importance of the target. The cross section for Coulomb excitation of the target is known with good precision and by determining the number of deexcitation counts coming from the target the number of incident polonium nuclei can be extracted using the same equation as before [Kes10]:

$$N_\gamma^{Pd}(2_1^+ \rightarrow 0_1^+) = \varepsilon_{MB,Pd} \cdot \sigma_{E2,Pd} \cdot \frac{\rho d N_A}{A} \cdot N_{Po} \quad (1.29)$$

The number extracted from equation 1.29 can then be used in equation 1.28 to calcu-

late the cross section. A way to circumvent this problem is to do a relative comparison with the number of gamma rays coming from the deexcitation of the target. The relative comparison of the beam and target excitation is then defined as the division of equation 1.28 by equation 1.29

$$\frac{N_{\gamma}^{Po}(2_1^+ \rightarrow 0_1^+)}{N_{\gamma}^{Pd}(2_1^+ \rightarrow 0_1^+)} = \frac{\varepsilon_{MB,Po} \cdot \sigma_{E2,Po}}{\varepsilon_{MB,Pd} \cdot \sigma_{E2,Pd}}. \quad (1.30)$$

Since the number of deexcitation counts and the absolute efficiencies for both target and projectile are known, and the cross section for Coulomb excitation is known for the target, $\varepsilon_{MB,Po}$ in equation 1.30 can be calculated.

1.4.5 X ray production

The gamma spectrum of a Coulomb excitation experiment does not only contain photo peaks coming from the deexcitation of a nucleus but a large amount of X rays are also present. These X rays are prompt and Doppler correction for the projectile is needed implying that they originate from the projectile while it is still in-flight.. These X rays can originate from either conversion electrons or collisions. The deexcitation of the populated states of the nucleus is not done necessarily through the emission of a gamma ray but also by conversion electrons. This will lead to the emission of characteristic X rays. In collisions, vacancies are created through the collision of a heavy ion beam on a target (heavy-ion induced vacancy creation), also leading to the emission of characteristic X rays. The Miniball detector can be used to detect these X rays but only high energetic X rays, coming from holes created in the K shell, can be detected. X rays originating from the higher-lying orbitals are too low in energy to be detected by the Miniball detector. The amount of X rays originating from converted transitions can be calculated using the conversion coefficients of the populated states. Using the total cross section for K-shell ionization, the amount of X rays originating from collisions can be estimated [Bre10]. Garcia et al. theoretically deduced that this cross section should depend on the proton number and energy of the projectile and the binding energy of the K electron [Gar73]. Romo-Kröger et al. advocated that the cross section for K ionization by an incident proton can be estimated by a fifth-order polynomial [Rom05]

$$\ln(\sigma I_K^2) = \sum_{i=0}^5 b_i (\ln(E_p/I_K))^i \quad (1.31)$$

where E_p is given in MeV, I_K in keV, the cross section in barn and $b_i = \{11.122, 0.6564, -0.5981, 0.0091, 0.0285, 0.006\}$. The cross section for proton-induced K-vacancy creation can be scaled to any heavy projectile, with proton number Z_p , energy E_p and atomic number A_p , by a scaling factor Z_p^2 . The cross section for any heavy projectile is then given by [Rom00]

$$\sigma_{proj}(E_p) = Z_p^2 \sigma_{proton}(E_p/A_p). \quad (1.32)$$

Equation 1.32 indicates that only the energy per nucleon is important for the calculation of the cross section. It is suggested to place a correction on the binding energy of the K electron in the target: replacing I_K with $I_K^{0.95}$. This corresponds to putting an effective charge for the target [Rom00]. Equation 1.31 together with equation 1.32 shows a dependence on the binding energy of the K electron, the proton number and energy of the projectile and thus confirm the previous work of Garcia et al. [Gar73]. The interest of this thesis lies not in X rays originating from the target but in X rays originating from the projectile. Therefore a change of reference frame is needed. The total energy in the center-of-mass frame is calculated to be [Ald75]:

$$E_{c.m.} = E_{lab,p} \frac{m_t}{m_t + m_p}$$

with $E_{lab,p}$ the energy of the projectile and m_p and m_t are the atomic mass of projectile and target. In both frames of reference the total energy in the center-of-mass frame should be equal. Thus when changing the reference frame between target and projectile, $E_{c.m.}$ remains unchanged. Using this condition, this gives the following equation:

$$\frac{E_{lab,Pd}}{m_{Pd}} = \frac{E_{lab,Po}}{m_{Po}}$$

meaning that the energy of the incoming projectile per unit of mass is unaltered.

Equation 1.32 still needs to be corrected for its intensity ratio and the fluorescence of the transition. The X rays are only detected when coincident with a particle detected in the DSSSD. The DSSSD only covers a limited angular range (see section 2.3.4) therefore a correction has to be applied since only part of the K-ionization cross section is measured. This correction is made possible due to the distinct dependence of the differential cross section for K vacancy creation on the scattering angle. The correction factor for the limited detector range is then inferred as the ratio of $\frac{\sigma_{66^\circ-142^\circ}}{\sigma_{0^\circ-180^\circ}}$ [Bre10].

It has been suggested in the paper of Nick Bree that the measured values for the K-vacancy cross section is lower than those predicted from theory. Therefore another important correction is applied to equation 1.32 [Bre10]. This correction factor is the ratio between the experimentally obtained cross section and the theoretical predicted ones. Due to the lack of experimental values for the cross section of K ionization for $^{202,206}\text{Po}$, this value has to be estimated. In the paper of Nick Bree this factor was estimated by considering experimentally inferred cross sections of other experiments and calculating the ratios. Figure 1.15 shows the result of his work. By looking at figure 1.15 a value of 0.070 ± 0.015 is taken as correction factor. Now an estimate can be made for the amount of X rays coming from K-vacancy production through collision [Bre10]:

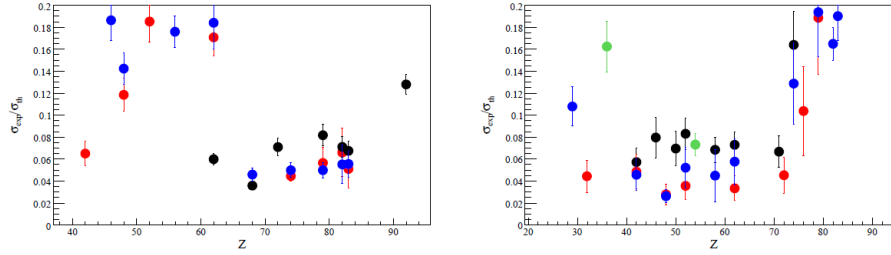


Figure 1.15 – Ratios between experimental and theoretically predicted K vacancy creation cross sections. Left: $A^{132}\text{Xe}$ projectile with energy with incident energy 3.6 MeV/u (black), 4.7 MeV/u (red) and 5.9 MeV/u (blue) inducing a K vacancy in a target with proton number Z . Right: $A^{208}\text{Pb}$ projectile with energy 3.6 MeV/u (black), 4.7 MeV/u (red), 5.9 MeV/u (blue) and 2.4 MeV/u (green) in which a K vacancy is created when colliding with a target with proton number Z [Bre10]

$$N_{K\alpha,estim} = \varepsilon_X S_{det} S_{exp} F I_{K\alpha} Z_t^2 \frac{1}{(I_K^{0.95})^2} \exp\left(\sum_{i=0}^5 b_i (\ln(E_p/I_K^{0.95}))^i\right) \frac{\rho d N_A}{A_t} I_b \quad (1.33)$$

where ε_X is the absolute detection efficiency at the energy of the emitted X ray, S_{det} the angular fraction of the total cross section covered by the DSSSD (i.e. 0.1346 ± 0.0017), S_{exp} the accepted factor for decreasing the theoretically calculated cross sections to empirical values (i.e. 0.070 ± 0.015), F the fluorescence of polonium, $I_{K\alpha}$ the relative intensity for K_α X rays, Z_t is the proton number of the target, I_K the binding energy of the K electron in keV, b_i the parameters used in the phenomenological curve, E_p the projectile energy per nucleon in the middle of the target in MeV, ρ the target density, d the target thickness, N_A the Avogadro number, A_t the atomic mass of the target and I_b the total dose of incident projectile ions on the target. The total amount of expected X rays is then the sum of the X rays coming from conversions and the amount of X rays coming from collisions [Bre10].

Equation 1.33 contains a number of correction factors, some of which are estimated by comparing to other experiments. However a lot of questions remain about the accuracy of these corrections (notably S_{exp} and S_{det}). Information about the K ionization cross section extracted from the $^{202,206}\text{Po}$ isotopes will provide more information on this matter. Especially information on the relation between the experimental cross section and theoretically estimated cross section is crucial in order to determine more accurate correction factors.

1.4.6 Computer code for the calculation of the cross sections

To calculate the cross sections of Coulomb excitation a computer program CLX can be used. CLX is a computer code written by H. Ower and adapted by J. Gerl and uses first-order perturbation theory in calculating the excitation cross sections [Ald75]. For the calculations a number of input parameters are required:

- The atomic number (Z) and mass number (A) of the target and projectile.
- The beam energy in MeV and the energy loss in the target in Mev/(mg/cm²)
- The target thickness in (mg/cm²)
- The angular coverage of the DSSSD in the center-of-mass frame for the scattered particle.
- The energies, spins and parities of the populated states.
- The matrix elements connecting these states.

After the calculation the CLX output file consists of the excitation cross section to each nuclear level, the differential cross section at specified angular mesh points and the elastic cross section. Please note that when performing the calculation the angular distribution of the γ rays is not taken into account.

Chapter 2

Experimental setup

As mentioned before, ^{202}Po and ^{206}Po were studied in this work. ^{202}Po was studied to gain information on the shape coexistence phenomenon in the polonium isotopes and ^{206}Po was studied to verify the X rays produced during the experiment. When performing experiments on exotic nuclei, the experimentalist is confronted with a number of difficulties during the production process of these exotic nuclei. They have extremely low production cross sections, very short half lives and there is an overwhelming production of unwanted species in the same target. Therefore possible production techniques are assessed on a number of features: the production rate, the efficiency and selectivity [VDu06]. In this section the experimental setup used to extract the data for this work is discussed. The Isotope Separation On Line technique (ISOL) offers the possibility to produce beams of exotic nuclei that are abundant, pure and of good quality. The $^{202,206}\text{Po}$ studied in this work were produced at the ISOLDE facility at CERN (Geneva). The isotopes were then post-accelerated to 2.85 MeV/u giving the ^{202}Po isotopes a total incident energy of 575.7 MeV and the ^{206}Po isotopes a total incident energy of 587.1 MeV when impinging on the target.

In this chapter the different parts of the experimental setup will be addressed and their operation will be briefly explained. Starting with explaining the production process of the $^{202,206}\text{Po}$ beams, this section follows the exotic beam as it makes its way through the experimental setup finally ending with the detection setup where the emitted gamma rays and the projectile and target are detected after the interaction. The extraction of the gamma-efficiency curve will also be described in this section. In the final section a motivation for using the ^{104}Pd and ^{94}Mo target will be given.

2.1 Creating the ion beam

A schematic layout of the radioactive ion beam facility HIE-ISOLDE is shown in figure 2.1 with the different parts in the beam line labeled. The different parts will now be

separately addressed and explained. This layout will be used in order to explain the basics of the REX-ISOLDE facility.

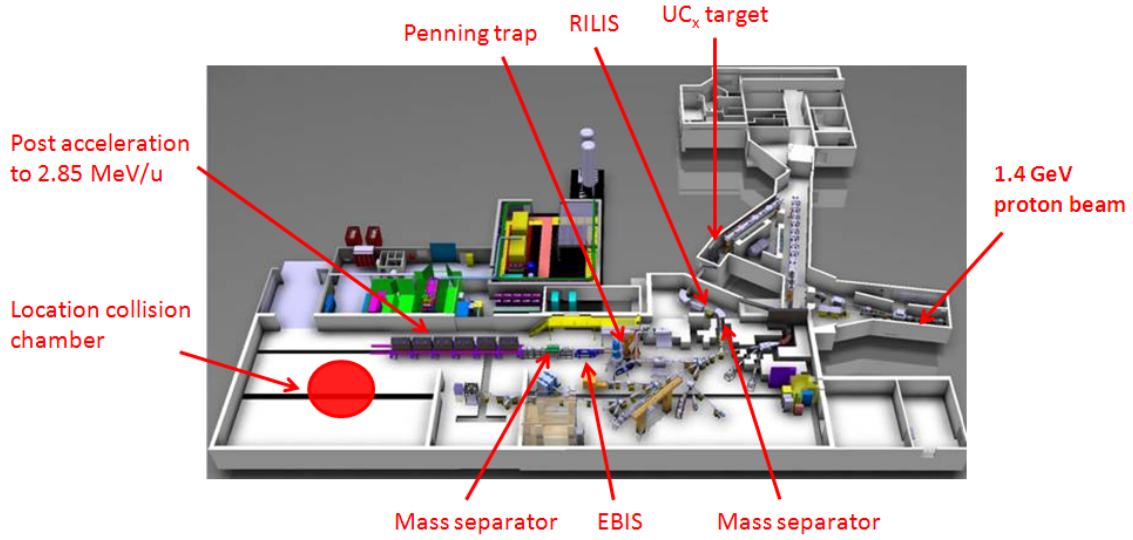


Figure 2.1 – A schematic layout of the HIE-ISOLDE facility.

PS Booster and target: The Proton Synchrotron Booster (PS booster) supplies a 1.4 GeV proton beam on a UC_x target (high-temperature thick target). The interaction of the energetic protons with the target induces nuclear reactions: fission, spallation and fragmentation. Typical targets have thicknesses of a few 100 g/cm^2 . In these reactions a wide range of nuclei are produced including a small fraction of the wanted isotope. The reaction products are fully stopped inside the target and slowly move out of the target by diffusion and effusion. The nuclei are then transported to the ion source via the transfer line. Both the transfer line and the target are kept at high temperature (typical temperature = 2000°C). This improves the diffusion and effusion process of the nuclei and avoids "sticking" of the nuclei to the walls of the target and transfer line. Important to note is that every chemical element has its own characteristic release time from the target to the transfer line.

The next step is the ionization of the neutral atoms. This is required to select the polonium isotopes and to simplify the post-acceleration process. At ISOLDE three ionization mechanisms are available: surface ionization, electron impact ionization and laser ionization. For this experiment the polonium isotopes were ionized using laser ionization.

RILIS: RILIS (Resonant Ionization Laser Ion Source) is one of the available ionization mechanisms at ISOLDE. In this process the atoms are excited stepwise by laser photons to a 1^+ charge state. The ionization process typically consists of two or three steps. By the sequential absorption of photons the electrons are excited to the continuum, to auto-ionizing states or to highly excited states. Figure 2.2 shows the ionization scheme used for ionizing the polonium isotopes. Most of these steps occur in resonance thus leading to a very efficient and chemically selective mechanism. Elements with a small

ionization potential can get ionized through collisions with the surface. This is one source of contamination. Another source of contamination is due to the bandwidth of the laser which might allow ionization of other elements. At this stage the beam consists of different polonium ions and some contamination. The beam of ions is then extracted by a 60 keV extraction electrode. The wanted isotope is then extracted from the low-energy ion beam by using a mass separator. The mass separator uses electromagnetic fields to select ions with the required A/q value (A = mass number and q = charge of the ion). For further details on the system see [RaAl]. The beam now contains only isotopes with a specific mass number (example: $A = 202$).

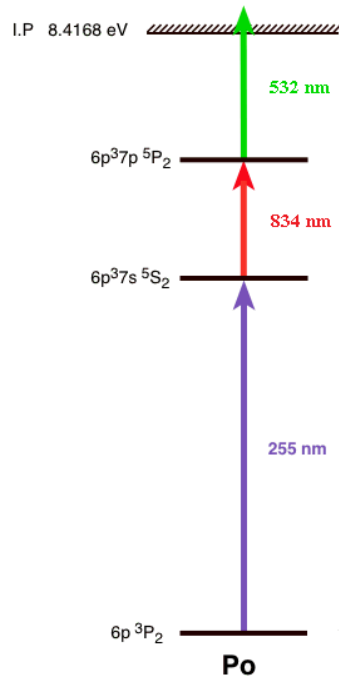


Figure 2.2 – The ionization scheme used to ionize the polonium atoms. The last step (510.6 nm) is not resonant. The ionization potential of the polonium atoms lies at 8.4168 eV [Ril12]

Once ionized the low-energetic, isobaric and singly-charged atoms are bunched, charge bred and post accelerated by REX-ISOLDE. This is efficiently done in four steps.

Penning trap: In the Penning trap the ion beam is cooled and bunched. The incoming ions are "captured" by a combination of electric and magnetic fields. During this process the ions are decelerated from 60 keV to several eV. Further deceleration is achieved by using a dilute buffer gas. Through collisions with this buffer gas the ions lose energy and are thus decelerated. Typically argon or neon gas is used under a pressure of approximately 10^{-3} mbar. The downside of using a gas is that it can be a source of contamination.

EBIS and mass separator: The Electron Beam Ion Source (EBIS) is used as a charge breeder. The initial charge state of 1^+ is increased to a n^+ state. EBIS consists of a strong

magnetic field that squeezes a high intensity electron beam along the field axis to a very small radius. The ions that are injected from the Penning trap are captured in a potential well created by an electrode structure. These ions are then bombarded with electrons from an electron beam. Under this continuous bombardment the ions get highly ionized. After a specific breeding time the desired charge state is reached and the trapping potential is lowered at the ejection side to release the ions. This charge multiplication process is used to simplify the acceleration process. But since the electron-impact ionization technique is not selective, buffer-gas atoms that escape the Penning trap are ionized as well leading to contamination of the beam. After the charge breeding the ion beam is injected into a second mass separator to reduce the level of contamination [VDu06].

REX linear accelerator: After the mass separator the ions get post accelerated to 2.85 MeV/u in the REX linear accelerator giving the ^{202}Po isotopes a total incident energy of 575.7 MeV and the ^{206}Po isotopes a total incident energy of 587.1 MeV. This beam is then sent onto the target in the collision chamber.

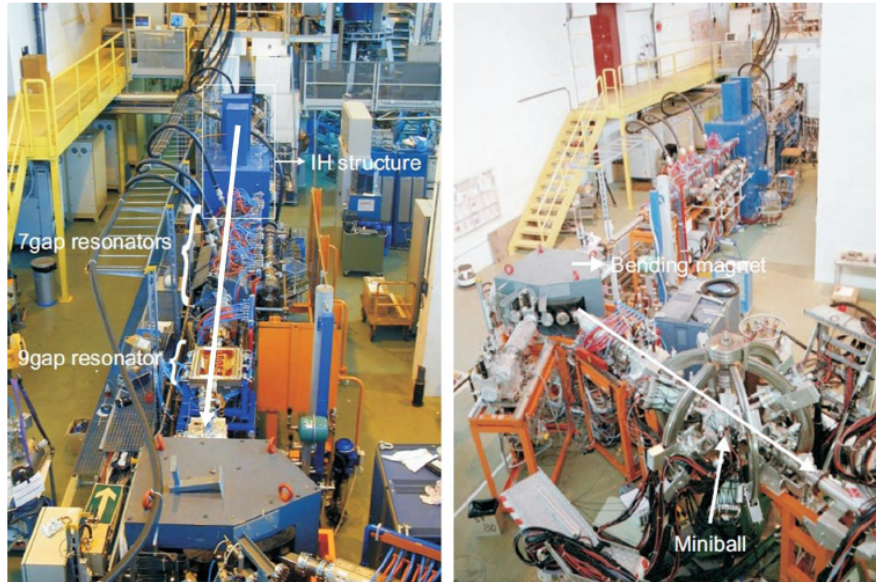


Figure 2.3 – This picture shows the linear accelerator at REX-ISOLDE that consists of three parts. The ions travel in the direction of the arrow. After post acceleration the ions are deflected into the Miniball detection setup, shown in the right picture [vdW06].

2.2 Time structure

Figure 2.4 shows the time structure of the experimental setup at REX-ISOLDE. This time structure has to be taken into account when analyzing the data. The PS booster delivers proton pulses to ISOLDE with a periodicity of 1.2 s. 12 of those proton pulses are then combined into a "supercycle" of 14.4 s. The continuous signal is then transformed into short bunches in the Penning Trap. These bunches are then injected into EBIS and

charge bred during 250 ms. The bunched signal coming from EBIS is then transported to the linear accelerator. Here the beam is accelerated by a voltage that is changing in time with resonant frequency.

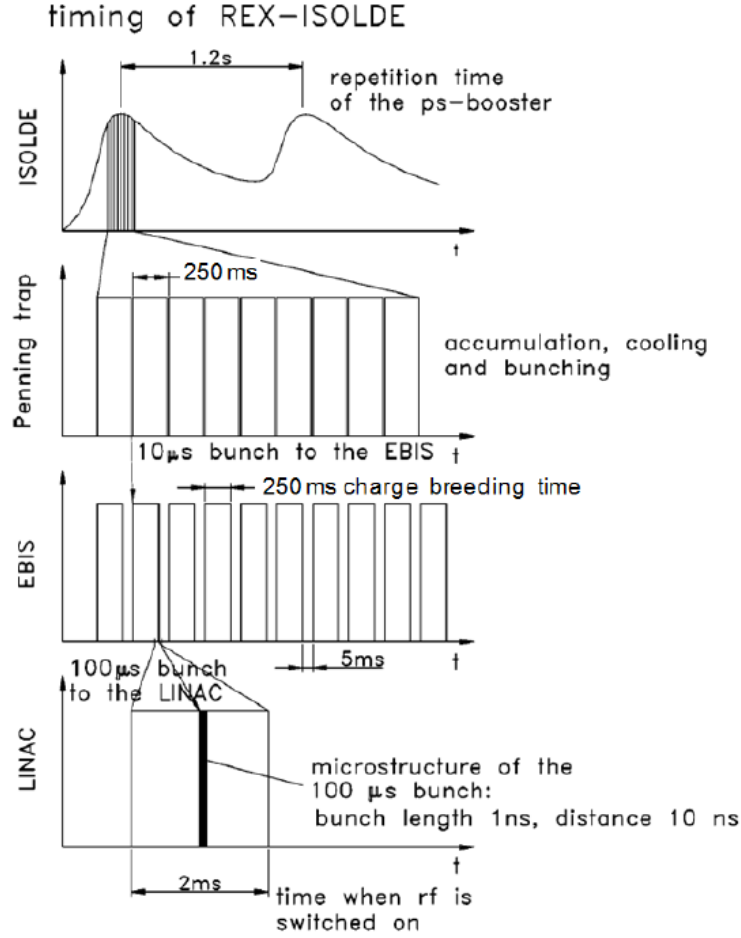


Figure 2.4 – Time structure of REX-ISOLDE [Hab00].

Miniball

Figure 2.5 shows the timing properties of the detection setup. When a gamma ray is detected in Miniball it will generate a coincidence gate of 800 ns (see figure 2.5 (E)). However, the DGF modules generate this trigger output some 500 ns after the detection of the gamma ray (see figure 2.5 (D)). This implies that the trigger for the particle detection needs to be delayed by roughly the same amount. In figure 2.5, A is the trigger of the particle detection. The delay time used is represented in figure 2.5 (B)) and a delayed particle trigger is generated (see figure 2.5 (C)). In the case that this delayed particle trigger lies within the coincidence gate, a coincident particle trigger is generated (see figure 2.5 (F)). This last trigger generates a gate of 1 μ s that is send to the ADC [War13].

In the Coulomb excitation experiment, the beam intensity is high ($>10^4$ ions/s) and therefore downscaling is applied. If no downscaling is applied, every particle will generate a gate. When downscaling is applied, the delayed particle trigger is downscaled by a user defined factor (for this work 2^4). This downscaling is not applied for the coincident particle trigger. This implies that all particle-gamma coincidences are recorded but the particles without a gamma ray (particle trigger falls outside the coincidence gate) are decreased by a factor of 16. The two right spectra in figure 2.5 show two examples. In the top spectrum, no downscaling is applied (all particles are accepted and no coincidence condition is applied). In the bottom spectrum the coincidence condition is applied and non-coincident particles, that lie outside the region indicated with *, are downscaled by a factor of 16 [War13].

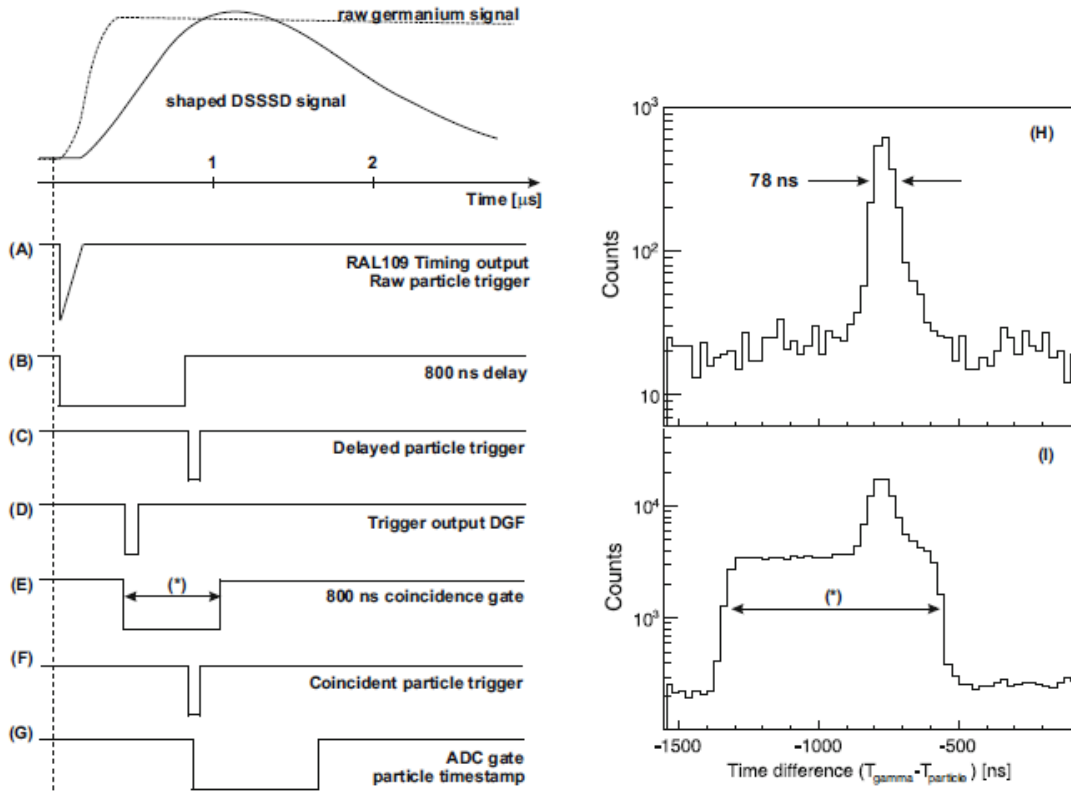


Figure 2.5 – The particle- γ coincidence scheme for Coulomb excitation. (A) timing signal of the scattered particle, (B) gate generated to delay the particle trigger (A), (C) is the delayed particle trigger, (D) is the trigger output of the DGF, (E) is the coincidence window of 800 ns opened by the detection of a gamma ray, (F) accepted particle trigger and (G) is the 1 μ s gate generated by each accepted particle trigger. (H) is the resulting time difference spectrum between particle and gamma ray when all particles are accepted. In (I) the coincidence condition is applied and the non-coincident particles (that lie outside the region marked with *) are downscaled by a factor of 2^4 [War13].

2.3 Detection system

As mentioned before, a bending magnet changes the trajectory of the post-accelerated $^{202,206}\text{Po}$ ions to let them impinge on the target, ^{104}Pd or ^{94}Mo , both with a thickness of 2 mg/cm^2 . The detection system used for the Coulomb excitation experiment consists of two parts, see figure 2.6. After collision with the target both the projectile and target nuclei are scattered elastically or inelastically. These scattered nuclei are then detected by a double-sided silicon strip detector (DSSSD). This detector is mounted inside the collision chamber. If one of the nuclei gets excited, the gamma rays that are emitted during de-excitation are detected by the Miniball gamma detector array which is placed in close geometry to increase the total detection efficiency. In the following section the Miniball gamma detector, the efficiency of the gamma detection and the DSSSD are described.

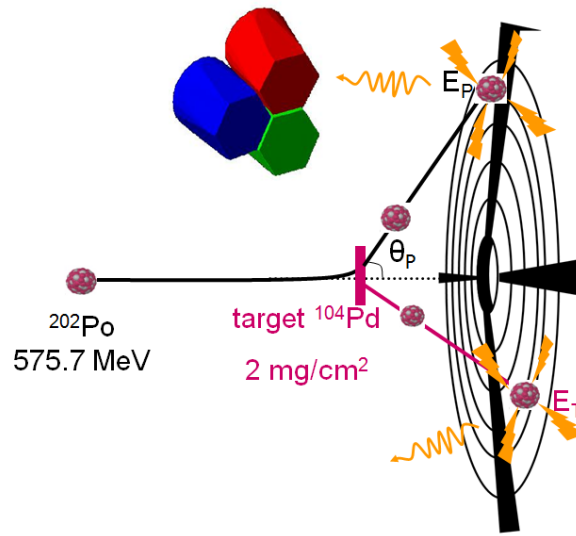


Figure 2.6 – Schematic overview of the Miniball detection setup used during the ^{202}Po run. For both targets the Miniball detection setup was the same. The scattered projectile and target nuclei are detected by the position-sensitive DSSSD. Gamma rays emitted during deexcitation are detected by the Miniball detector array. During the run only 7 of the 8 clusters were mounted [Bre06].

2.3.1 The Miniball γ -detector array

The Miniball detector array consists of 8 clusters of detectors (7 were mounted during the experiment). Every cluster consists of three individually encapsulated HyperPure Germanium crystals (HPGe) which are surrounded by an aluminum cap. Since the gamma ray coming from the projectile or target is emitted in flight the energy of the gamma ray will be Doppler shifted. In order to be able to correct for this shift the detectors need to be position sensitive. This position sensitivity is achieved by dividing each crystal into six segments and one central electrode. This way a total segmentation of $(7 \cdot 3 \cdot 6 =) 126$ is achieved. Since the optimal working temperature of the crystals is low, they are mounted on cold fingers at liquid nitrogen temperature ($\approx 70\text{ K}$). The clusters are placed on four

flexible aluminum arms so they can be positioned in the θ (angle with the beam axis), α (spin around the cluster angle) and ϕ (cone around the beam axis) directions.

2.3.2 Germanium cluster calibration

An emitted photon that hits a germanium detector deposits its energy inside the crystal and creates electron-hole pairs in the semiconducting material. Under the influence of an electric field, the electron-hole pairs will move in opposite directions and travel to the electrodes. This will result in a measurable pulse that can be detected by an outer circuit. After proper signal processing the magnitude of the generated electrical current is associated with a channel number. As the degree of nonlinearity is small for the Miniball detectors, there will be a linear relation between the energy of the incoming gamma ray and the number of created electron-hole pairs [Kno10]:

$$E = a + b \cdot C. \quad (2.1)$$

E is the energy of the incoming photon and C is the channel number. The only unknowns are the parameters a and b. These are determined through the calibration of the germanium detectors.

As mentioned before the Miniball spectrometer consists of 8 germanium clusters, 7 of which were mounted during the experiment. The calibration needs to be done for every segment and every core of the germanium detectors of the Miniball spectrometer. The calibration of the cores was done manually while for the segments an automated calibration was done. For the calibration of the germanium detectors two sources were used: ^{133}Ba and ^{152}Eu . ^{152}Eu decays by β^+/EC to ^{152}Sm and by β^- decay to ^{152}Gd . ^{133}Ba decays to ^{133}Cs by β^+/EC decay. The gamma rays following the decay of these sources provide enough photopeaks over the interested energy range. Especially the barium source provides enough gamma rays in the low-energy part making a good calibration of the low-energy part possible. This is desired as X rays constitute an important part of the analysis. In this section the calibration method will be explained for one core of the germanium detector. The data is taken from the third core of cluster 4. First the uncalibrated spectrum of the core is plotted, see figure 2.7.

The spectrum of this core shows a number of photopeaks. These photopeaks need to be associated with the energy of an incoming gamma ray. For the calibration the most intense photopeaks are chosen. These chosen photopeaks must span the interested energy range. To acquire a decent calibration for the low-energy part enough photopeaks below 100 keV are selected. The chosen photopeaks are fitted with a Gaussian function with linear background to determine the mean channel number:

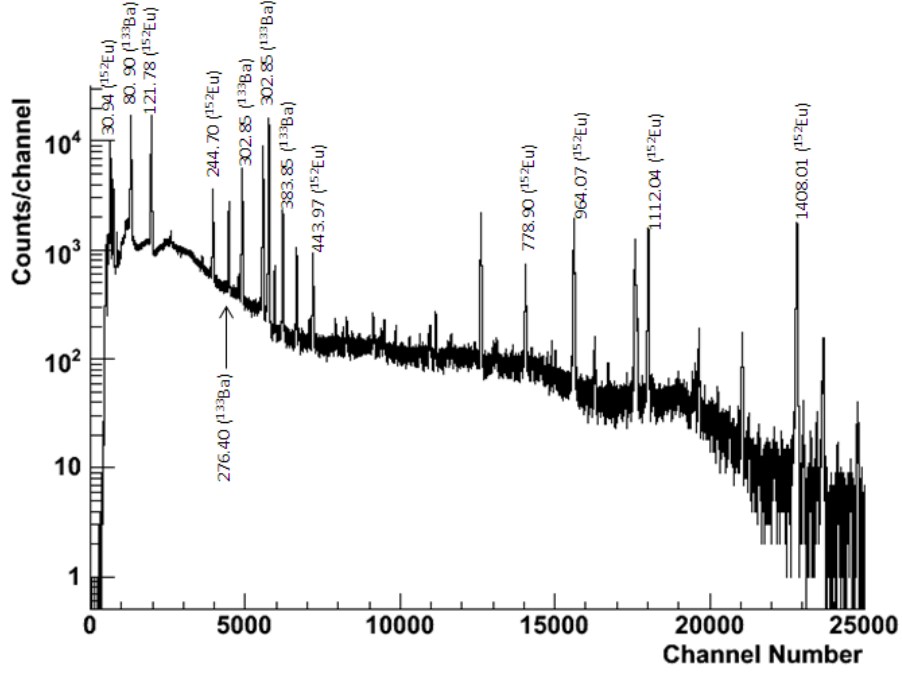


Figure 2.7 – This graph shows the number of counts as a function of the channel number. To obtain this graph the decay of a ^{133}Ba and a ^{152}Eu source was used. The data is taken from the third core of cluster 4. The mean channel number for a photopeak was extracted by fitting with a Gaussian function with linear background.

$$f = p_0 + p_1 \cdot x + p_3 \exp\left(-\frac{(x - p_4)^2}{2 \cdot p_2^2}\right) \quad (2.2)$$

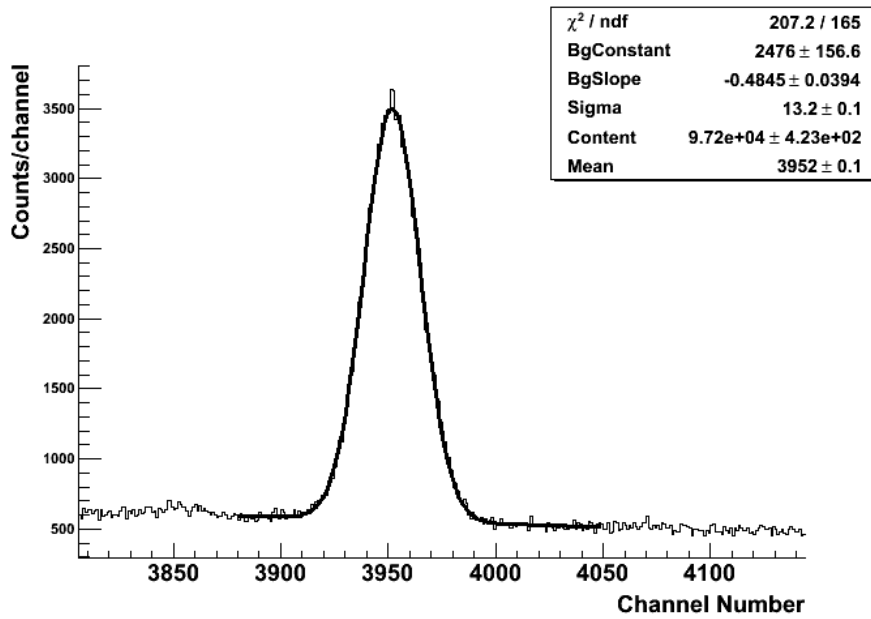


Figure 2.8 – Gaussian fit with linear background for one peak corresponding to an energy of 244.6975 keV. Fit parameters are shown on the graph [nndc].

The first two parameters (p_0 and p_1) are the background constant and slope, p_2 is the gauss width, p_3 is the gauss constant and p_4 is the gauss mean. Fitting with this function will give the mean channel number and corresponding error.

Fig 2.8 shows a typical fit for one photopeak together with the fit parameters. A linear fit is then performed of the energies as a function of the channel number. When performing a linear fit using the errors deduced from the fit with a Gaussian function with linear background, the reduced chi-square (χ_{red}^2) of the linear fit is very high (in this case = 299.566). The χ_{red}^2 is used as a measure for the goodness of the fit. In principle a $\chi_{red}^2 = 1$ indicates that the extent of the match between the data and the fit is in accord with the error variance. Because of the small error on the channel number the error on the gain and offset of the linear fit will be small as well. This will result in a large χ_{red}^2 value. The value of χ_{red}^2 can be decreased by increasing the error on the mean channel number. Note that increasing the error on the channel number will also increase the error on the gain and offset. This was performed following the standard procedure of multiplying the error on the channel number with the $\sqrt{\chi_{red}^2}$. These scaled errors on the channel number are inserted in the fitting program and the linear fit is performed again, see figure 2.9, and resulted in a χ_{red}^2 of 1.4.

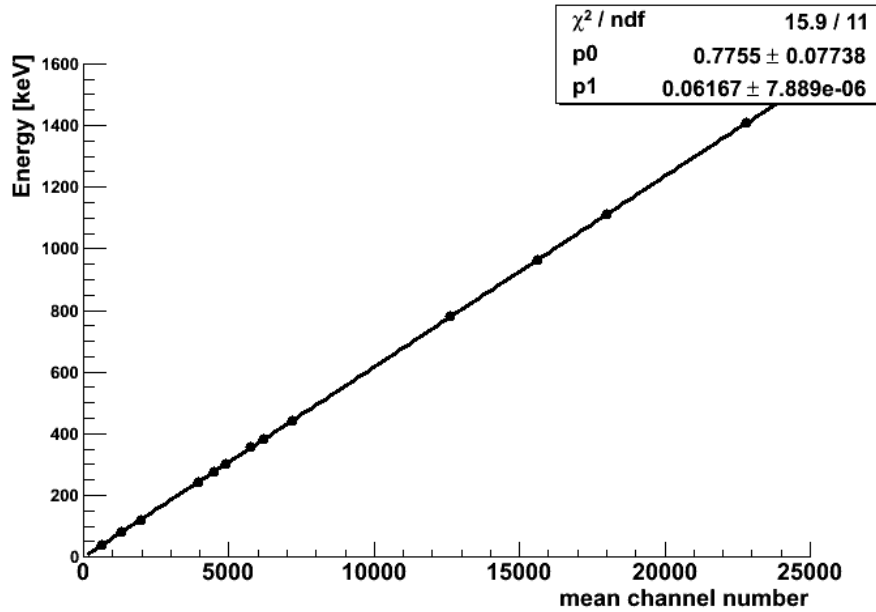


Figure 2.9 – Linear fit of the data points (error bars included). The fit parameters are shown in the top right corner.

From the fit the parameters a and b of equation 2.1 can be extracted including the error on these. This procedure is then repeated for every germanium detector of each of the the seven clusters.

2.3.3 Efficiency of the γ detection

An absolute efficiency curve for the Miniball gamma detector in its configuration used during the experiment (September 2012, IS479) was determined by analyzing the gamma spectra taken with two different radioactive sources: ^{133}Ba (13.9 kBq) and ^{152}Eu (15.5 kBq). ^{152}Eu decays by β^+/EC to ^{152}Sm and by β^- decay to ^{152}Gd . ^{133}Ba decays to ^{133}Cs by β^+/EC decay. The energy of the gamma rays coming from the excited daughter nuclei after the decay span a large energy range. But especially at low energy numerous peaks are observed in the obtained spectrum. This allows to extract the absolute efficiency at low energy as well. This section explains the different steps in extracting the absolute efficiency curve from the data. First the relative detection efficiencies of the gamma rays are determined. Using coincidence data the absolute efficiencies for certain transitions are determined in the following step. The data for the absolute efficiency is split up into two regimes: the absolute efficiencies at energies below 200 keV and the absolute efficiencies at energies above 200 keV. Both regimes are fitted separately to obtain the absolute efficiency curve.

Relative efficiency

To determine the relative detection efficiencies of the gamma rays, the gamma spectrum of the decay of ^{133}Ba and ^{152}Eu is plotted (see figure 2.10). Values for the relative detection efficiency can be calculated by dividing the integrals of the photo peaks by the corresponding relative intensities (Note: in this case the relative intensity is defined as the theoretical number of gamma rays per 100 decays) [Chu99]. In table 2.1 the energies of the gamma rays and their corresponding relative efficiencies (including error bar) are shown. The two transitions at 39.94 keV and 45.59 keV are X rays coming from the Eu source. These two were included as well in the analysis because they provide information on the low energy part of the spectrum.

Absolute efficiency

In order to calculate the absolute efficiency of the detection setup different gamma cascades in the decay of ^{133}Ba and ^{152}Eu are considered (see figure 2.11). The detection efficiency of γ_1 and γ_2 can then be calculated by counting the number of γ_2 transitions that are in coincidence with γ_1 . The detection efficiency of γ_1 is given by [Kes10]:

$$\varepsilon_{\gamma_1} = \frac{N_{\gamma_1\gamma_2}(1 + \alpha_{\gamma_1})}{\frac{6}{7}N_{\gamma_2}I_{\gamma_1}(1 + \alpha_{\gamma_1})} \cdot \sum_i^{E_2 \rightarrow \dots} \left(I_{\gamma_i}(1 + \alpha_{\gamma_i}) \right). \quad (2.3)$$

$N_{\gamma_1\gamma_2}$ is the number of γ_2 transitions that are in coincidence with γ_1 , α_{γ_i} is the total internal conversion coefficient of γ_i and $I_{\gamma_i}(1 + \alpha_{\gamma_i})$ is the total relative intensity of γ_i . The summation runs over all paths that depopulate level E_2 , this includes γ_2 . The correction

¹⁵² Eu		¹³³ Ba	
Energy [keV]	ε_{rel}	Energy [keV]	ε_{rel}
39.940 (5)	4.20 (8)	53.1622 (6)	12.1 (4)
45.660 (6)	8.3 (2)	80.895 (2)	22.0 (2)
121.7871 (3)	26.29 (7)	160.612 (2)	24.5 (12)
244.6975 (8)	20.5 (1)	223.237 (1)	19.5 (11)
344.279 (1)	18.0 (3)	276.399 (1)	17.4 (2)
443.965 (5)	15.1 (2)	302.8508 (5)	16.8 (1)
778.904 (2)	11.73 (4)	356.0129 (7)	15.65 (5)
867.378 (4)	10.8 (1)	383.849 (1)	15.1 (1)
964.07 (2)	10.43 (4)		
1085.83 (3)	10.20 (6)		
1112.035 (4)	9.75 (4)		
1299.14 (1)	8.8 (2)		
1408.006 (3)	8.61 (3)		

Table 2.1 – This table shows the calculated relative efficiency for the gamma rays from the decay of ¹³³Ba and ¹⁵²Eu. The relative efficiency is expressed in arbitrary units. The values are multiplied by a constant factor: in this case 10^{-4} . At this point the relative efficiency of the two sources cannot be compared to one another. Only comparisons between gamma transitions of one source yield any significance.

factor $\frac{6}{7}$ comes from the addback mode used during data analysis. In addback mode coincident gammas with an energy higher then 100 keV are summed when incident in the same cluster. In this mode the cluster is said to be "blocked" for the detection of the coincident gamma ray. Since there were only 7 clusters mounted during the experiment this leaves 6 clusters available for the detection of the coincident gamma ray thus giving rise to a correction factor of $\frac{6}{7}$. However, when considering coincidences with a gamma with an energy below 100 keV (e.g. 80.89 keV), addback will be absent leaving more detectors able of detecting the coincident gamma. The correction factor in this case will be $\frac{20}{21}$. The detection efficiency of γ_2 can be calculated in a similar way [Kes10]:

$$\varepsilon_{\gamma_2} = \frac{N_{\gamma_1\gamma_2}(1 + \alpha_{\gamma_2})}{\frac{6}{7}N_{\gamma_1}I_{\gamma_2}(1 + \alpha_{\gamma_2})} \cdot \sum_i^{E_2 \rightarrow \dots} \left(I_{\gamma_i}(1 + \alpha_{\gamma_i}) \right). \quad (2.4)$$

The absolute detection efficiency of both gammas in the cascade can hence be determined using formula 2.3 and 2.4. These absolute detection efficiencies are compared to the relative efficiencies using a "scaling factor". This scaling factor is defined as the ratio of the absolute efficiency to the relative efficiency: $\frac{\varepsilon_{abs}}{\varepsilon_{rel}}$. In this thesis for each source two gamma cascades were selected. In table 2.2 the coincidences with their calculated scaling factors are shown. A weighted average of the scaling factors is then calculated and used to scale the relative efficiencies to obtain values for the absolute detection efficiencies (see table 2.3).

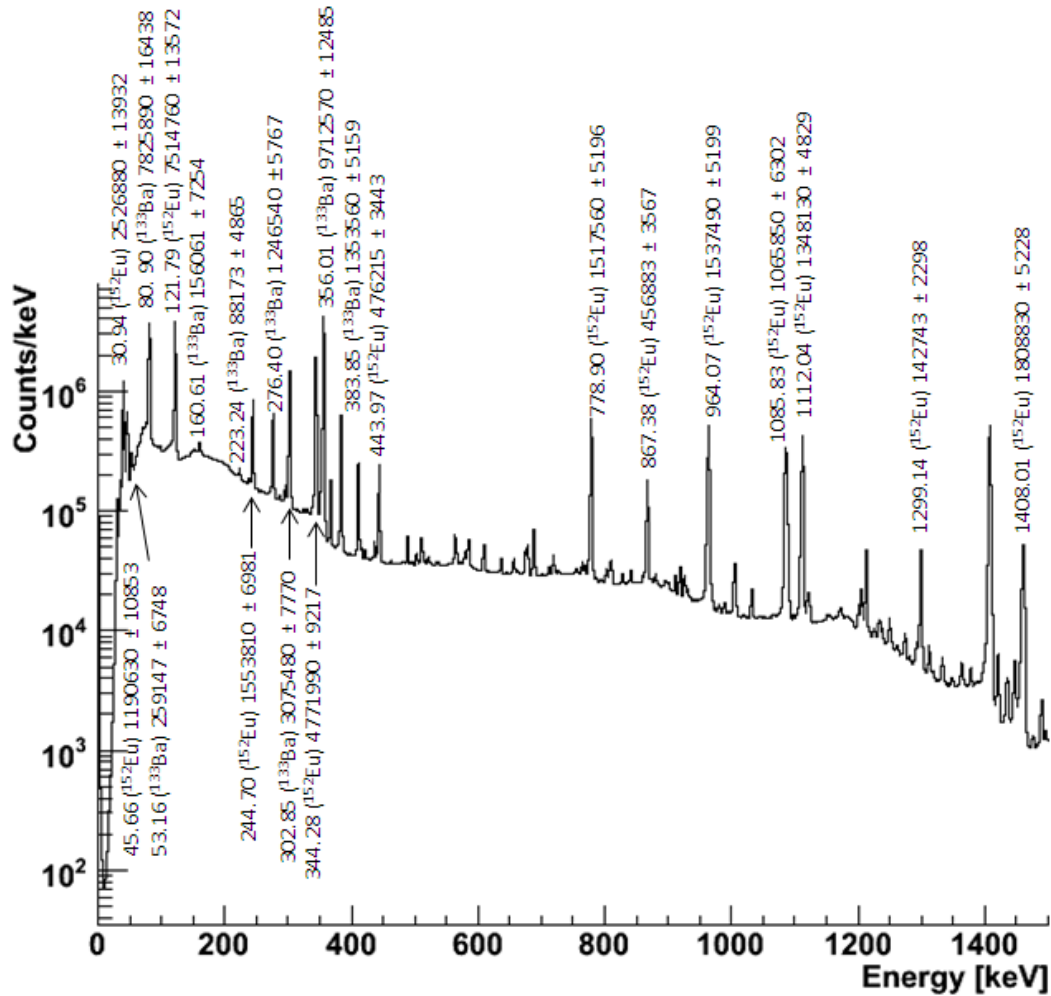


Figure 2.10 – The calibrated gamma-energy spectrum of the decay of ^{133}Ba and ^{152}Eu . The number of counts is displayed on a logarithmic scale. This gamma spectrum is taken after the Coulomb excitation experiment. Gammas that coincided with background radiation from the radioactive decay of the beam or its daughters used in the experiment were left out of the data analysis. An example is the 688.67 keV gamma ray coming from the β^+/EC decay of ^{152}Eu to ^{152}Sm . It coincided with the 688.957 keV gamma ray coming from the decay of ^{200}Tl to ^{200}Hg . In case that two (or more) gammas lie too close in energy to be resolved, a weighted average is used during further analysis. For instance the gamma rays of 1084 keV and 1085.869 keV coming from the decay of ^{152}Eu , yield an average value of 1085.8 keV.

To obtain an absolute efficiency curve these points need to be fitted. As to determine the absolute efficiency curve the energy range was divided into a low-energy part (<200 keV) and a high-energy part (>200 keV). In the high-energy part the logarithm of the absolute efficiencies behaves linearly with respect to the energy of the gamma ray [Kno10]:

$$\ln(\varepsilon) = p_0 + p_1 \cdot \ln(E/700). \quad (2.5)$$

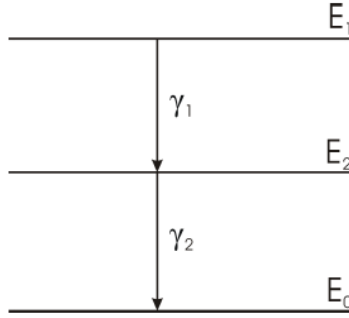


Figure 2.11 – A gamma cascade. The two gammas (γ_1 and γ_2) can be seen in coincidence if the lifetime of level E_2 is short enough ($< \mu s$).

^{152}Eu			^{133}Ba		
E_γ [keV]	$E_{\gamma\text{coin}}$ [keV]	$\varepsilon_{\text{abs}}/\varepsilon_{\text{rel}}$	E_γ [keV]	$E_{\gamma\text{coin}}$ [keV]	$\varepsilon_{\text{abs}}/\varepsilon_{\text{rel}}$
121.7871	1408.006	0.00776 (3)	80.895	305.8508	0.00839 (8)
1408.006	121.7871	0.00776 (4)	80.895	356.0129	0.00829 (3)
344.279	778.904	0.00767 (4)	302.8508	80.895	0.00841 (9)
778.904	344.279	0.0077 (5)	356.0129	80.895	0.00830 (3)
		0.00774 (2)			0.00830 (2)
		$\chi_{\text{red}}^2 = 1$			$\chi_{\text{red}}^2 = 1$

Table 2.2 – This table shows the scaling factors that have been calculated using different coincidences in the decay of ^{152}Eu and ^{133}Ba . The absolute efficiency for the transition E_γ is calculated by considering coincidences with the γ ray with energy $E_{\gamma\text{coin}}$. The resulting absolute efficiency can be compared to the relative efficiency and the scaling factor can be determined. In bold is the weighted average of the different scaling factors.

^{152}Eu		^{133}Ba	
Energy [keV]	ε_{abs} [%]	Energy [keV]	ε_{abs} [%]
39.940 (5)	3.25 (6)	53.1622 (6)	10.1 (3)
45.660 (6)	6.4 (1)	80.895 (2)	18.3 (2)
121.7871 (3)	20.35 (8)	160.612 (2)	20.31 (96)
244.6975 (8)	15.9 (1)	223.237 (1)	16.2 (9)
344.279 (1)	13.9 (2)	276.399 (1)	14.5 (1)
443.965 (5)	11.7 (1)	302.8508 (5)	13.9 (1)
778.904 (2)	9.08 (4)	356.0129 (7)	12.99 (5)
867.378 (4)	8.33 (8)	383.849 (1)	12.6 (1)
964.07 (2)	8.07 (4)		
1085.83 (3)	7.89 (5)		
1112.035 (4)	7.54 (4)		
1299.14 (1)	6.8 (1)		
1408.006 (3)	6.67 (3)		

Table 2.3 – This table shows the calculated absolute efficiency (in percentages) for the gamma rays coming from the decay of ^{133}Ba and ^{152}Eu using the scaling factors (see table 2.2).

The energy is divided by 700 to decrease the error on the offset parameter p_0 . When performing a linear fit, the error on the offset parameter can become high if the "zero point" (= intercept with the vertical axis) lies far from the data points. This problem is avoided by fitting as a function of $(x - A)$ with A a value close to the x values of the data points. This way the "zero point" is artificially brought closer to the data points and the error on the offset decreases. In the logarithmic case this translates to fitting as a function of $\ln(x/A)$.

First the absolute efficiencies of the high-energy points of ^{152}Eu are fitted using the simple exponential function, equation 2.5 (see figure 2.12). From the fit p_0 and p_1 are extracted: $p_0 = 2.25 \pm 0.01$ and $p_1 = -0.494 \pm 0.014$. Up to now only the higher-energy points of the ^{152}Eu decay were fitted. The higher-energy points coming from the ^{133}Ba decay still need to be included. In order to keep the error on the final results as small as possible, the relative efficiencies of the higher-energy points are fitted in stead of the absolute efficiencies. The slope of the fit is demanded to be the same as that of the Eu fit because the relative efficiencies only need to be shifted by a constant to become absolute efficiencies. The fit function used for fitting the higher-energy points of ^{133}Ba is then:

$$\ln(\varepsilon) = p_0 - 0.494 \cdot \ln(E/700). \quad (2.6)$$

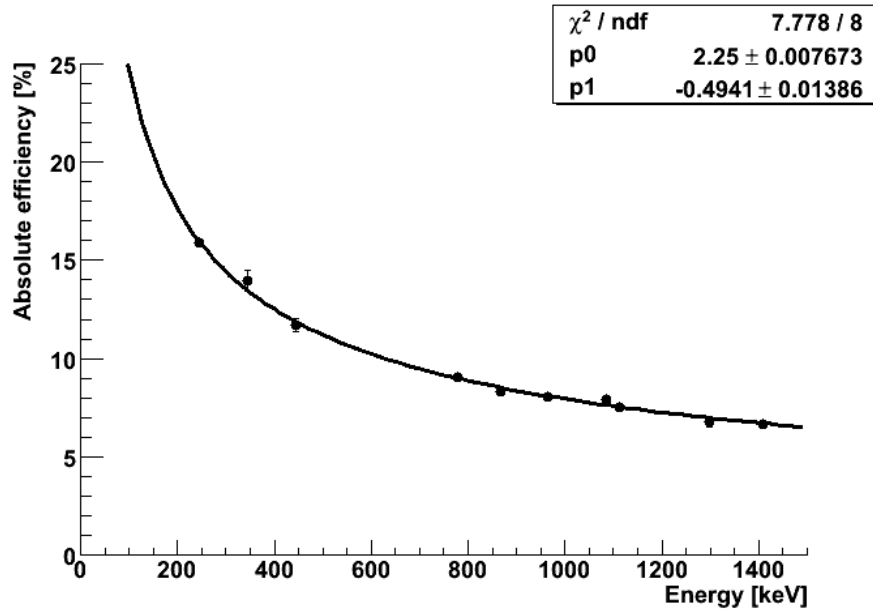


Figure 2.12 – Fit of the absolute efficiency of the higher-energy points of the ^{152}Eu decay with a simple exponential function. The fit parameters are shown in the top right corner.

The resulting fit is shown in figure 2.13¹. The offset is found to be: $p_0 = 7.019 \pm 0.003$. The relative efficiencies of the ^{133}Ba source can then be rescaled to obtain absolute efficiencies using:

¹The errors were rescaled using the $\sqrt{\chi^2_{\text{red}}}$ resulting in more realistic errors on the fit parameters.

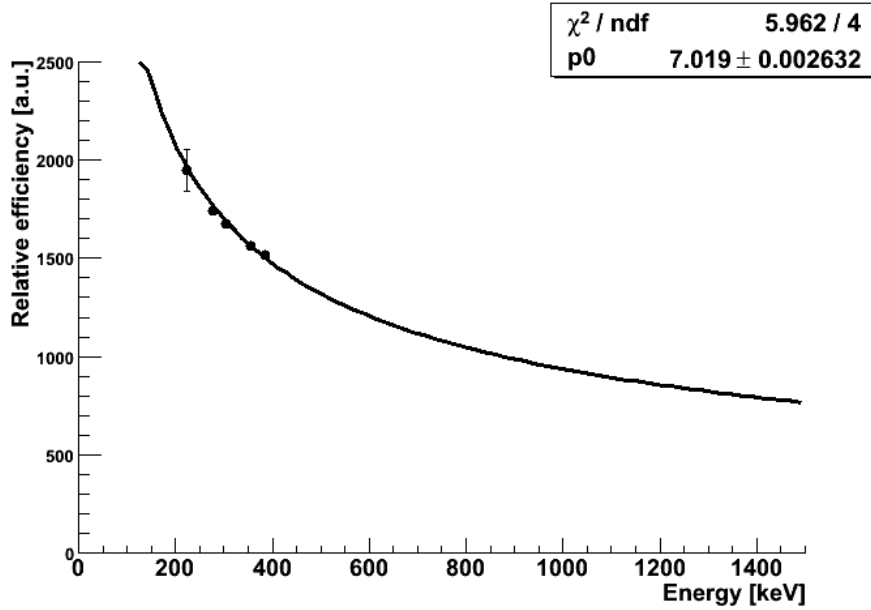


Figure 2.13 – Fit of the relative efficiencies of the higher-energy points of the ^{133}Ba decay. These points are fitted with a simple exponential function demanding that the slope is the same as the europium fit in figure 2.12. The fit parameters are shown in the top right corner.

$$\ln(\varepsilon_{abs}) = \ln(\varepsilon_{rel}) + (2.25 - 7.019). \quad (2.7)$$

All the higher-energy points from ^{152}Eu and the rescaled ^{133}Ba can now be fitted together to obtain an absolute efficiency curve that describes the absolute efficiency at energies higher than 200 keV. The resulting fit is shown in figure 2.14¹. From the fit p_0 and p_1 are again extracted: $p_0 = 2.250 \pm 0.006$ and $p_1 = -0.493 \pm 0.010$.

When the absolute efficiencies of the lower-energy points are included as well, a multi-parameter fit has to be used [Kno10]:

$$\ln(\varepsilon_{abs}) = p_0 + p_1 \cdot \ln(E/200) + p_2 \cdot (\ln(E/200))^2 + p_3 \cdot (\ln(E/200))^3 + p_4 \cdot (\ln(E/200))^4. \quad (2.8)$$

The efficiency increases for decreasing energies. For low energies the absolute efficiency reaches a maximum before decreasing for higher energies. The higher-order terms in the multi-parameter fit determine the shape of this turnover point. Figure 2.15² shows the result of this fit. Again the energies are divided by a constant to decrease the errors on the fit parameters. The division constant in this case was not so clear. Dividing by a too large constant will result in a large error for the lower-energy points but dividing by a too small constant will yield large errors for the higher-energy points. Therefore the relative

²The errors were rescaled using the $\sqrt{\chi_{red}^2}$ resulting in more realistic errors on the fit parameters.

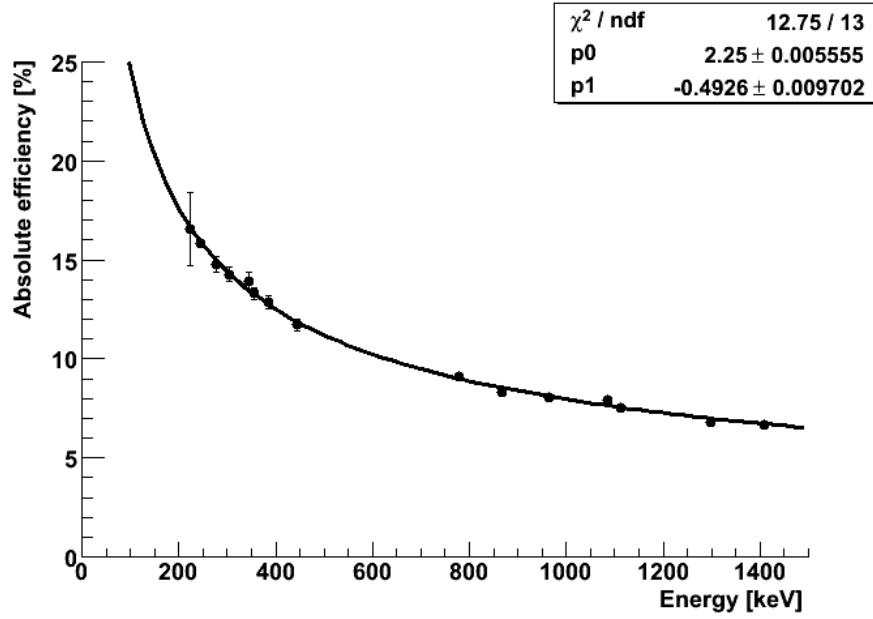


Figure 2.14 – Fit of the absolute efficiencies of the higher-energy points ($E > 200$ keV) of ^{152}Eu and the rescaled points of ^{133}Ba . The fit parameters are shown in the top right corner.

errors for different A factors are compared and the A factor was chosen which gave the smallest relative error throughout the interesting energy range of this work.

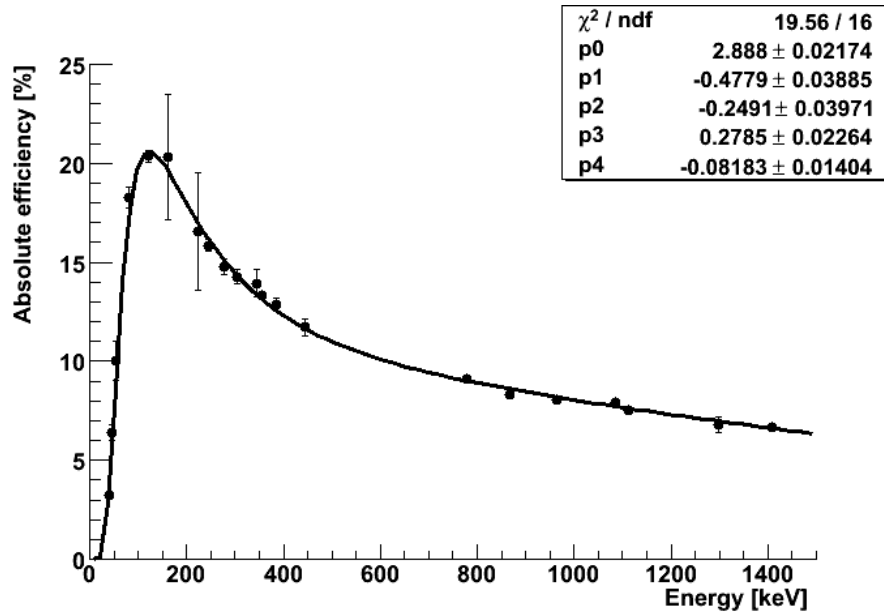


Figure 2.15 – All the absolute efficiency points (higher-energy ^{152}Eu and rescaled ^{133}Ba points plus the lower-energy points from both sources) fitted with the function given in equation 2.8. The fit parameters are shown in the top right corner.

The final absolute efficiency curve is hence obtained by combining the fit at energies above 200 keV with the multi-parameter fit for the energies below 200 keV, the result of

which is shown in figure 2.17.

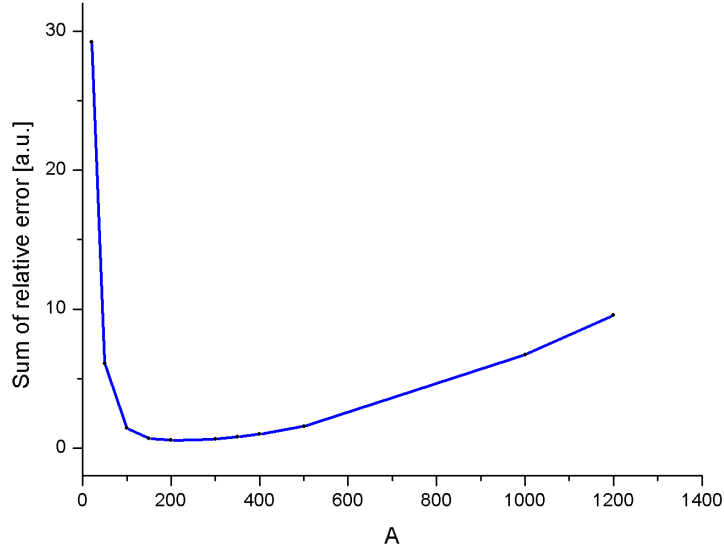


Figure 2.16 – The relative error on the absolute efficiency for different energies (40, 70, 100, 200, 500 and 1000 keV) with the same A factor are summed and plotted. The x axis shows the A factor used in the fit with $\ln(E/A)$. The minimum in the curve represents the A value for which the overall relative error on the absolute efficiency is the lowest, in this case $A = 200$.

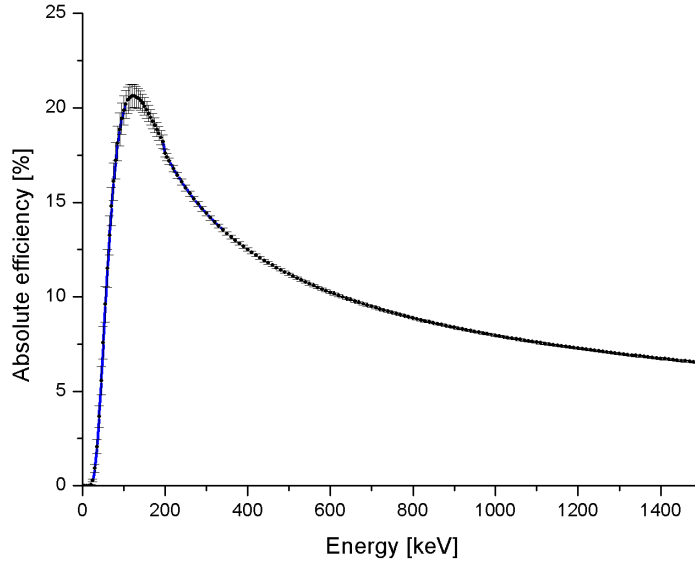


Figure 2.17 – The absolute efficiency curve representing the absolute efficiency for different energies. This curve is the combination of the multi-parameter fit for low energies and the linear fit for higher energies.

2.3.4 Double-sided silicon-strip detector

The double-sided silicon-strip detector (DSSSD) serves as a particle detector and is mounted inside the collision chamber. Figure 2.18 shows a schematic picture of the DSSSD. The detector is divided into four independent quadrants and consists of a front and rear face, as shown in the figure. Each quadrant consists of a silicon wafer with a thickness between $476\ \mu\text{m}$ and $481\ \mu\text{m}$. The front face is divided into 16 annular strips and the back face is divided into 24 sector strips. In most Coulomb excitation experiments, the sector strips are coupled pairwise [War13]. This segmentation makes the DSSSD position sensitive as is required for Doppler correction of the emitted γ ray. For this work the following naming convention is used: strip number 15 corresponds to the strip at the largest scattering angle in the laboratory frame (outer strip) and strip number 0 corresponds to the strip at the smallest scattering angle in the laboratory frame (inner strip).

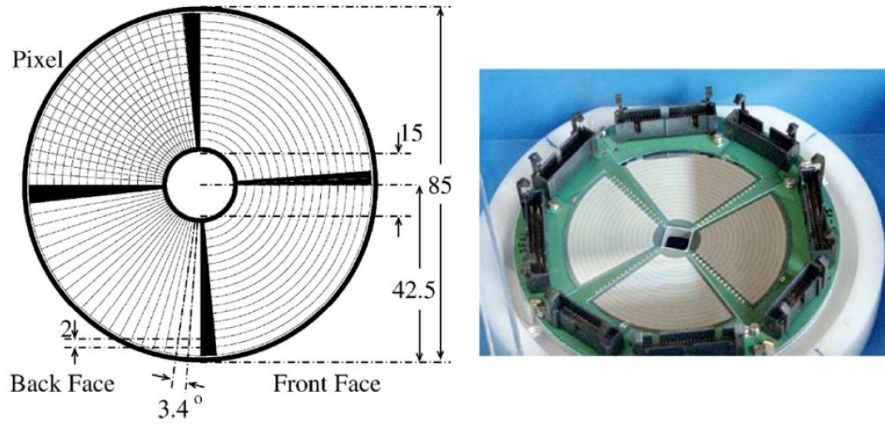


Figure 2.18 – Schematic picture of the double-sided silicon strip detector [Ost02].

The distance between the target and the DSSSD was 26.5 mm. From the distance between the target and the DSSSD and the pitch of the annular strip, the minimal and maximal scattering angles in the lab frame can be calculated: 18.8° and 57.1° . Since the energy and mass of the incoming beam and the mass of the target are known, the laboratory scattering angles can be translated to the center-of-mass frame using equation 1.11. Table 2.4 gives an overview of the angular ranges for the target and projectile in the center-of-mass frame. The scattering angle of the projectile in the laboratory frame is much lower than the target nuclei. This comes from the fact that the projectile is much heavier than the target and thus its trajectory will be less effected by the collision than the trajectory of the lighter target nucleus. Figure 2.19 visualizes the relation between the laboratory and the center-of-mass scattering angles for the scattering of ^{202}Po on ^{94}Mo .

When traveling through the target the projectile will lose its energy. A consequence of this is that there is a minimal energy for the polonium isotope to escape the target. Therefore the scattering angle in the center-of-mass frame is also limited by the minimal energy needed to escape the target. When the scattering takes place at the end of the

Projectile	Target	CM range projectile	CM range target
^{202}Po	^{104}Pd	$58^\circ - 140^\circ$	$66^\circ - 142^\circ$
^{202}Po	^{94}Mo	$63^\circ - 144^\circ$	$66^\circ - 142^\circ$
^{206}Po	^{104}Pd	$59^\circ - 142^\circ$	$66^\circ - 142^\circ$

Table 2.4 – Center-of-mass ranges for target and projectile for the three experiments.

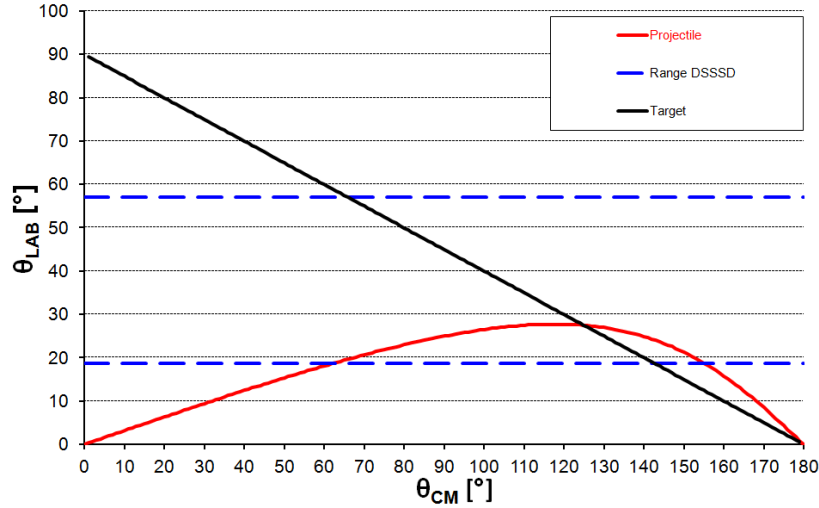


Figure 2.19 – The relation between the scattering angle in the laboratory frame θ_{LAB} and the scattering angle in the center-of-mass frame θ_{CM} for a ^{202}Po projectile on a ^{94}Mo target for both the projectile and target. The blue dotted line is the range of the DSSSD in the laboratory frame.

target, the polonium isotope will probably have enough energy to escape the target. But in the other extreme case, when the interaction takes places immediately when the polonium ion encounters a target nucleus, the polonium ion might not have enough energy to escape the target. To calculate the minimal energy needed to escape the target, the energy loss of the $^{202,206}\text{Po}$ ion inside the ^{94}Mo and/or ^{104}Pd target needs to be determined. This is done via the programme SRIM, a programme used for the calculation of the stopping power and range of ions in matter [Zie13]. The results of the SRIM calculations are shown in table 2.5. Figure 2.20 shows the energy of the projectile and target in the laboratory frame as a function of the scattering angle in the center-of-mass frame. Also indicated is the minimal energy needed for the projectile to escape the target. If one takes the extreme case of scattering in the beginning of the target, it is clear that the polonium isotope does not have enough energy to escape the target for the higher scattering angles in the center-of-mass frame.

2.3.5 Energy Calibration of the DSSSD

A particle that hits the detector will deposit its energy in the silicon wafer and produce electron-hole pairs. As explained in the previous section, the number of created electron-hole pairs will be proportional to the energy of the incoming particle. Thus a linear

Projectile	Target	Stopping power [$\frac{\text{MeV}}{\text{mg/cm}^2}$]	$E_{\min}$ [MeV]
^{202}Po	^{104}Pd	59	118
^{202}Po	^{94}Mo	61	122
^{206}Po	^{104}Pd	59	118

Table 2.5 – Result of the SRIM calculations showing the stopping power for each experiment and the minimal energy ($E_{\min}$) to escape the target when interaction occurs immediately when the polonium ion encounters a target nucleus [Zie13].

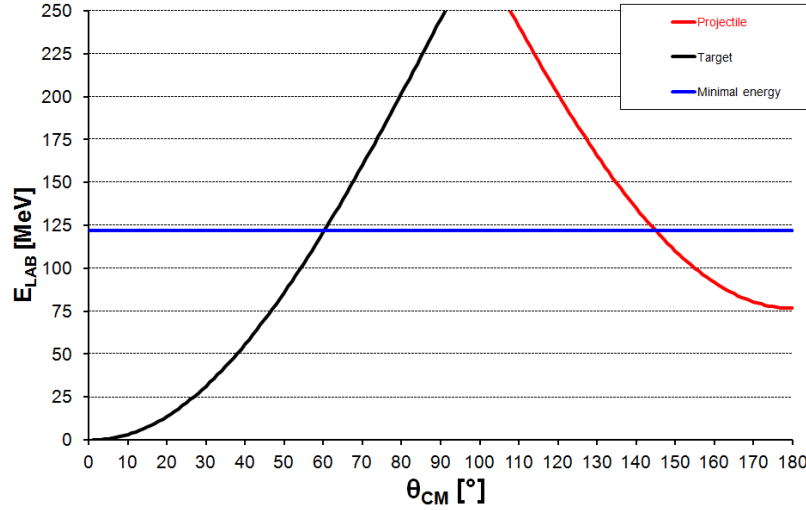


Figure 2.20 – The energy of the projectile and target in the laboratory frame in relation to the scattering angle in the center-of-mass frame for a ^{202}Po projectile on a ^{94}Mo target. The blue line represents the minimal energy for the projectile to be able to travel through the ^{94}Mo target (2 mg/cm^2)

behavior between the channel number and energy is expected. Again the parameters a and b of equation 2.1 need to be determined for every annular strip of every quadrant of the DSSSD. So in total $(4 \cdot 16) = 64$ sets of parameters need to be extracted. These parameters are extracted by using two energy points. When calculating the energy of the detected particle two processes need to be taken into account. Due to considerations regarding kinematics the energy of the detected particle will vary with the annular strip number (detection angle). Also the energy loss of the particle in the target needs to be calculated and corrected for. The energy loss can be calculated using SRIM [Zie13].

The first energy point was obtained by analyzing the scattering process of ^{40}Ar on ^{196}Pt . A stable ^{40}Ar beam was accelerated to 2.85 MeV/u ($=114 \text{ MeV}$). The energy of the scattered ^{40}Ar particles varies from 82 MeV at the outer strip to 98 MeV at the inner strips. The loss in energy when travelling through the target has been taken into account and is on average equal to 14 MeV . The distance a ^{40}Ar travels through the target depends on the angle of the scattering process. Ions scattered in the front have to travel a larger distance through the target than ions scattered in the back. Therefore ions scattered in the back of the target have a higher energy after leaving the target than ions scattered in the front of the target. Figure 2.21 shows the spectrum that was used to calibrate the

fifth annular strip of the first quadrant. Clearly visible is the ^{40}Ar peak. The peak is broadened due to energy straggling in the target.

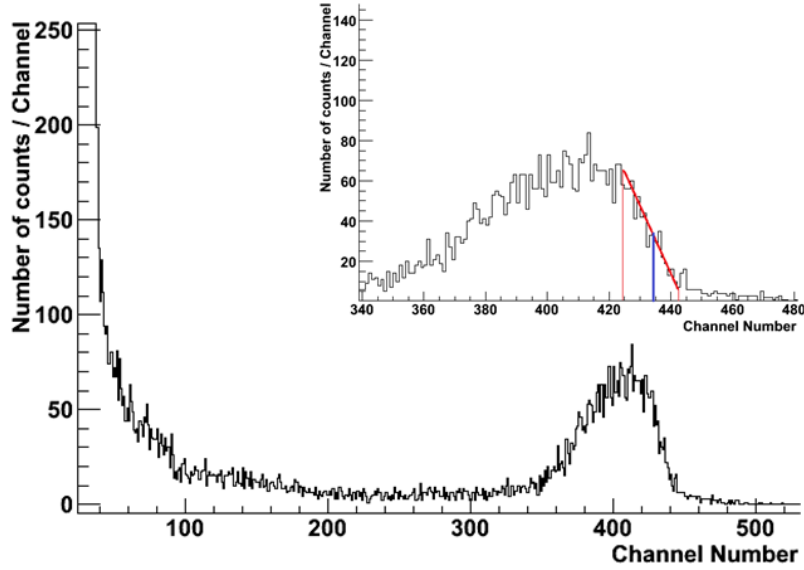


Figure 2.21 – This graph shows the number of detected ^{40}Ar particles as a function of the channel number used for the calibration of strip five of the first quadrant. The low energy part in the spectrum is due to noise in the detector. A zoom on the peak is shown as well showing the employed calibration method. The value extracted for this strip equals 433.

From this spectrum, the calibration point is extracted. For this calibration, it was assumed that the scattering process takes place in the back of the target. As mentioned before these ions have a higher energy and are thus responsible for the high-energy part of the peak shown in the spectrum. The high-energy tail of the peak in the corresponding spectrum follows approximately a linear trend thus it can be approximated by a linear function. This approximation is shown in red in both figure 2.21 and 2.22. The starting point and end point of this linear trend is estimated and the average value of both is taken as the calibration point for this strip (shown in blue in both figure 2.21 and 2.22).

The second energy point is obtained by analyzing the scattering process of ^{202}Po on ^{104}Pd . This is a classical scattering process and thus the kinematics are fully known. For the second energy point the ^{104}Pd particles were chosen since the ^{104}Pd particles are detected throughout the entire angular range of the detector. Thus the calibration is based on a low-energy point (^{40}Ar) and a high-energy point (^{104}Pd). This makes extrapolation to high energies in the Coulomb-excitation experiment unnecessary. The calibration method employed is the same as explained before. Figure 2.22 shows the spectrum that was used to calibrate the fifth annular strip of the first quadrant. The energy of the detected ^{104}Pd varies from 125 MeV in the outer strip to 368 MeV in the most inner strip. In the outer strips the ^{104}Pd peak is clearly present. In the inner strips however, the ^{104}Pd peak is difficult to distinguish from the ^{202}Po peak due to their close proximity to each other and the limited resolution of the DSSSD. Since the ^{202}Po peak is better visible in the 3 inner

strips, the ^{202}Po particles are chosen for the calibration of these strips. In these strips the energy of the detected ^{202}Po particle varies from 263 MeV for the larger laboratory scattering angles to 352 MeV in the most inner strip.

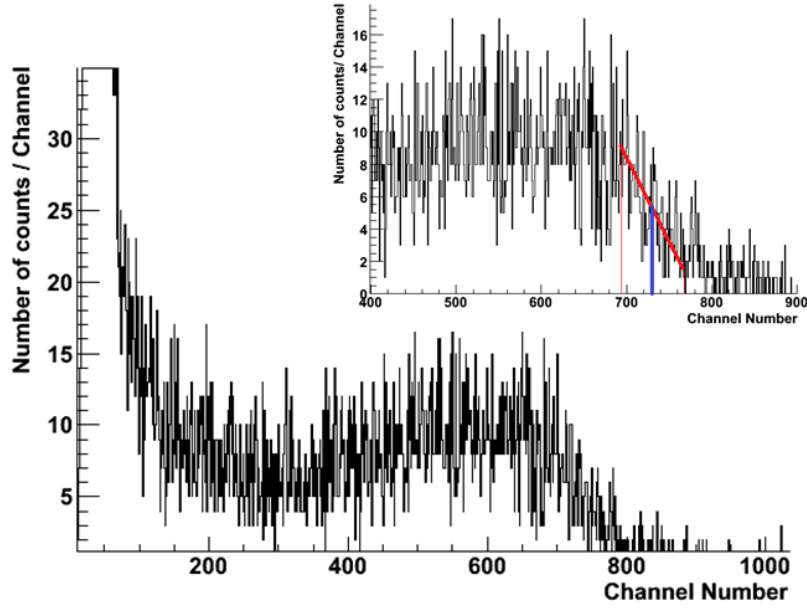


Figure 2.22 – This graph shows the number of detected ^{104}Pd particles as a function of the channel number used for the calibration of strip five of the first quadrant. The low energy part in the spectrum is due to noise in the detector. A zoom on the peak is shown as well showing the employed calibration method. The value extracted for this strip equals 737.

This procedure is repeated for every strip in every quadrant of the DSSSD. Using the obtained channel number and corresponding energies the parameters a and b of equation 2.1 can be calculated as:

$$a = E_{Pd} - b \cdot C_{Pd}$$

$$b = \frac{E_{Pd} - E_{Ar}}{C_{Pd} - C_{Ar}}$$

2.4 The Targets

To conclude this section about the experimental setup a few words need to be said about the proper choice of target. The choice of the target is a crucial step for a successful Coulomb-excitation experiment. There are a few criteria which can be used to find a suitable target. First of all the target nucleus needs to be stable (this is the case for both the ^{104}Pd target and ^{94}Mo target). Second the energies of the deexcitation gamma rays of projectile and target must differ enough so that they can be discriminated during the further analysis. Figure 2.23 shows the deexcitation gamma rays coming from the polonium isotopes and the two different targets. From these level schemes it is clear

that the second condition is fulfilled for both targets. The third condition involves the kinematics of the reaction: the projectile and target nuclei falling on the DSSSD need to be distinguishable. This condition is checked by performing a simulation of the energy of the detected nuclei (see figure 2.24). Figure 2.24 shows that a separation between target and projectile is possible for the 12 most outer strips. For the 4 most inner strips, target and projectile kinematics overlap making it difficult to distinguish between the two. This has to be taken into account during further analysis. Finally, to be able to perform a relative comparison between the projectile and target excitation, the target nucleus has to be collective enough in order to observe a sufficient amount of target excitation. Also the transitional matrix elements connecting the populated states of the target need to be well known in order to perform this comparison. By checking all these criteria a suitable target nucleus can be found.

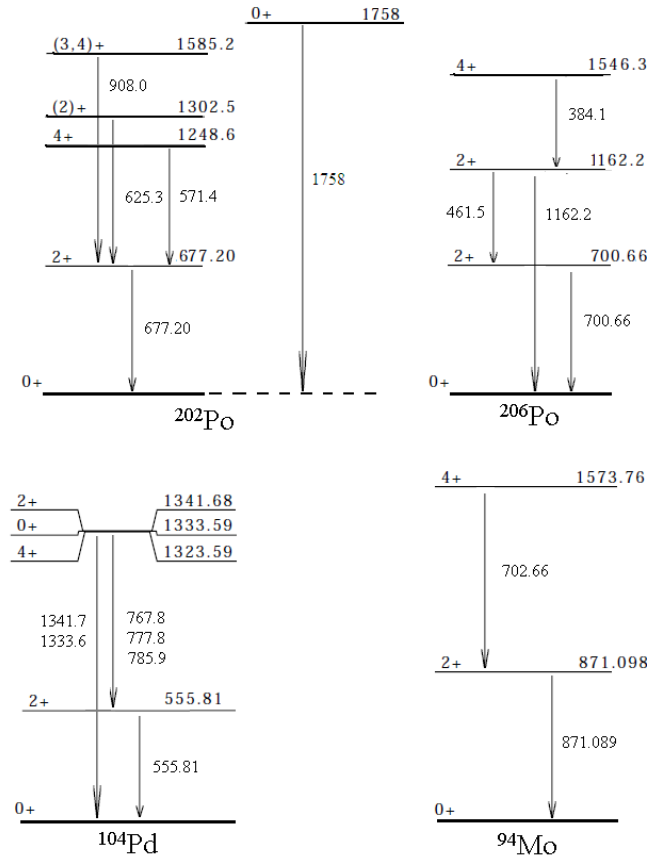


Figure 2.23 – The level schemes of the low lying excited states in $^{202,206}\text{Po}$, ^{104}Pd and ^{94}Mo . The transitions of ^{202}Po are the transitions observed in the β^+/EC -decay study of ^{202}Po by Bijmens et al. [Bij98], [nndc].

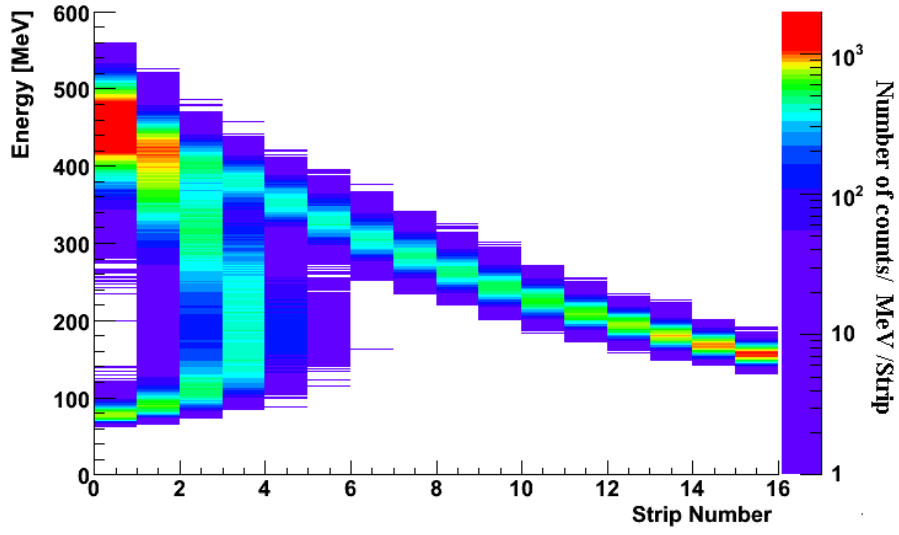


Figure 2.24 – The simulated number of detected particles in function of the energy and the strip number for a ^{202}Po projectile on a ^{104}Pd target. In this calculation it was assumed that the beam was perfectly centered with a beam spot of only 9mm^2 .

Chapter 3

Data Analysis

This chapter explains the different steps in analyzing the data from the Coulomb excitation experiment of ^{202}Po and ^{206}Po performed at CERN in September 2012. For ^{202}Po , two targets were used: a ^{104}Pd target and a ^{94}Mo target. For ^{206}Po only the ^{104}Pd target was used. The chapter starts with a short introduction about the kinematics of a Coulomb excitation experiment and explains how the beam purity was determined. After this introduction the different steps in selecting the Coulomb excitation events from the background is addressed. From the Doppler-corrected spectra, obtained after the selection, the information on the cross section for Coulomb excitation of ^{202}Po is extracted. Using the CLX code, the matrix element connecting the populated low-lying states is determined. An important part will deal with the X-ray analysis. A large amount of X rays were present in the spectra of ^{202}Po . In order to gain more insight into this matter the ^{206}Po data was analyzed and compared to the ^{202}Po data.

3.1 Kinematics

A Coulomb-excitation event consists of the detection of two particles scattered back-to-back in the center-of-mass frame in coincidence with a gamma ray. The energy of the detected particle can be plotted as a function of the strip number. Figure 3.1 shows a typical example of such a plot. This spectrum can be compared to the one expected from simulations. The difference in energy between the experimental and simulated spectra is due to the loss in energy of the nuclei when traveling through the target. This loss in energy is not taken into account in the simulated spectra. Both spectra show a clear separation between projectile and target kinematics except for the most inner strips. By selecting two-particle events, separation between target and projectile in the kinematics spectrum can be further increased. The motivation for using this two-particle method is twofold [Kes10]. Since the kinematics is precisely known target and projectile can easily be labeled in the kinematics spectrum. Using this information, each time a combination of a projectile and a target particle can be selected thus assuring the identification of the correct particle in every two-particle event. The second advantage concerns the fact that

the conditions for every selected event are the same. Thus an efficiency correction for the particle detection is not required. However as will be explained in the following section, a problem with the downscaling resulted in a loss of statistics and rendered this type of event selection nearly impossible for the three experiments analyzed in this work.

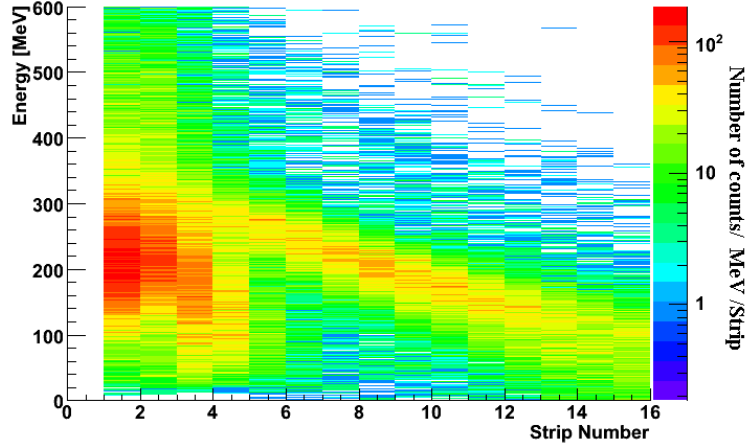


Figure 3.1 – Energy versus strip number for all events for the ^{202}Po on ^{104}Pd experiment. The intensity is plotted in logarithmic scale. The experimental spectrum can then be compared with the spectrum obtained from simulation.

The first step in selecting the Coulomb excitation events is identifying the correct particles that originate from such an event. When looking at the spectrum in figure 3.1, the target and the projectile kinematics are clearly visible as well as the separation between these two. This was desired in order to identify the nuclei. Using the kinematics spectrum an energy gate can be determined for the target and projectile nuclei. This energy gate indicates, for each strip of the DSSSD separately, the minimal and maximal energy of a detected target or projectile nuclei originating from a Coulomb excitation event. Only particles with energies that fall into these energy gates are selected for further analysis. This particle energy gate is thus the first condition in selecting the Coulomb excitation events. As can be seen from figure 3.1, the target and projectile kinematics overlap in the most inner strips of the DSSSD leading to problems in the identification of the target and projectile nucleus. This overlap was also visible in the other two experiments. This problem was circumvented by using an extra selection condition for the target nuclei. Besides an energy gate, it was requested that the target particle was detected in one of the 12 most outer strips of the DSSSD. Therefore events in the 4 most inner strips were ignored. This avoided the problem of mis-identification between target and projectile.

As already explained in Chapter 1, the Coulomb excitation cross section depends in second order on the diagonal matrix element of the first excited state. This will result in small deviations in the cross section as a function of the scattering angle for Coulomb excitation. In order to gain sensitivity on this effect, the cross section is calculated for different angular ranges of the DSSSD. The polonium isotopes only cover the small laboratory scattering angles due to backbending. The target nuclei however are scattered

throughout the entire range of the DSSSD, see figure 3.1, and therefore make a perfect "guide" for scanning the center-of-mass range.

Beam purity

As mentioned in Chapter 2 the polonium beam can suffer from contamination. Section 2.1 already indicated that the buffer gas used in the Penning trap could be one source of contamination. Another source of contamination is the production of other elements in the UC_x target. These elements could possibly survive the mass separation and are also impinging on the target. Thus target excitation could come from either the polonium isotopes or the contamination. Therefore the beam purity needs to be determined and the number of counts coming from target deexcitation need to be corrected for this contamination.

The beam purity represents the percentage of the total target excitation induced by the polonium isotopes compared to the total target excitation induced by contaminants in the beam. During the experiment Laser ON/OFF measurements were made to be able to determine the beam purity. In laser ON/OFF runs, the laser is periodically switched between ON mode, in which case the polonium isotopes will get ionized, and OFF mode, in which case no laser ionization of polonium takes place. During laser ON, the beam will consist of polonium isotopes and contamination whereas in laser OFF, the beam will only contain contamination. Thus during laser OFF mode no polonium isotopes were incident on the target such that target excitation could only occur through inelastic scattering with contaminants in the beam. The spectrum for laser ON mode and laser OFF mode can be plotted and compared to each other, see figure 3.2. Next an integration window is selected around the target peak, in figure 3.2 around the palladium peak, and the number of counts in this window is determined in both spectra. From the ratio of these two numbers, the percentage of the total target excitation coming from the contamination can be extracted. Once known, the beam purity can be calculated using the following formula: $\text{beam purity} = 1 - \frac{\text{Counts}_{OFF}}{\text{Counts}_{ON}}$.

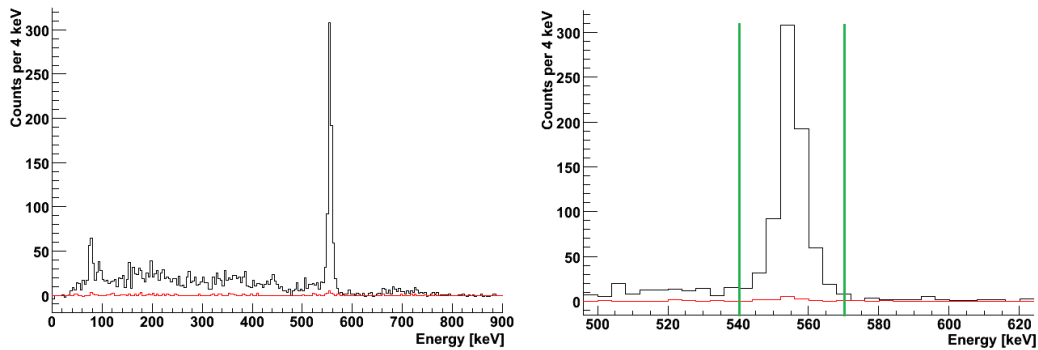


Figure 3.2 – Figure showing the comparison between the laser ON (black) and the laser OFF (red) spectrum for the ^{206}Po on ^{104}Pd experiment. On the right is a zoom of the region around the palladium peak with the integration window around the peak indicated in green.

The beam purity was determined for the three experiments yielding a value of $98 \pm 2\%$ beam purity for the two experiments using ^{202}Po as projectile, and a value of $94 \pm 1\%$ for the the experiments using ^{206}Po as projectile. The value for the ^{206}Po is lower than for the ^{202}Po experiments. Due to maintenance of the PS booster the proton beam was switched off during the ^{206}Po experiment and the residual isotopes present in the target were simply extracted by increasing the target heating. The increase in target temperature will lead to an increase in temperature of the laser ionization tube. This could possible increase the probability of the surface ionization process and thus lead to an increase in contamination of the ^{206}Po beam.

3.2 Prompt and random window determination

After a Coulomb-excitation event either the projectile or target (or both) can be in an excited state. The nucleus will then de-excite by emitting a γ ray. The time between excitation and deexcitation depends on the lifetime of the excited state but is typically on the order of ps. The detection of this γ ray in the Miniball cluster is then coincident with the detection of the two particles in the DSSSD. Such a γ ray that is coincident with two particles in the DSSSD is called "prompt" (two-particle event). However, due to the limited detection range of the DSSSD the two particles will not always be detected. Therefore γ rays coincident with one particle are also called "prompt" (one-particle event). If a γ ray is not coincident with a particle it is defined as "random". Random γ rays have different origins. They can originate from bremsstrahlung, background radiation or β decay of the radioactive projectile and its daughter products. Another possibility is that the γ ray does come from a Coulomb-excitation event but neither of the two particles are detected in the DSSSD due to its limited detection range. This deexcitation γ ray can then be coincident with a random particle.

In order to distinguish between a prompt and a random gamma ray, a prompt and random time window have to be chosen. For this the time between the detection of an event in the Miniball detector and the detection of the coincident event in the DSSSD is plotted. The prompt time window contains a lower and upper limit for the time difference between the detection of a particle and the detection of the gamma ray. A typical time difference spectrum $T_\gamma - T_{particle}$ is shown in figure 3.3 for each quadrant separately of the DSSSD.

The peaks visible in the time difference spectra contain the prompt events, all the rest are random events. In figure 3.3 a problem is immediately visible in quadrant 1 and 2. In quadrant 3 and 4, this prompt peak lies on a large plateau of random events but in quadrant 1 and 2, this plateau is shifted away from the peak, with the peak also reduced in intensity. A further investigation learned that the problem lies in the coincidence window. As explained in section 2.2, non-coincident particles are downscaled by a factor of 16. In quadrant 1 and 2 this coincident window around the DGF trigger was wrongly set leading to a downscaling of the actual "prompt" events meaning that only 1 in 16 prompt events are recorded. This error in the downscaling will influence the data analysis as well. It was

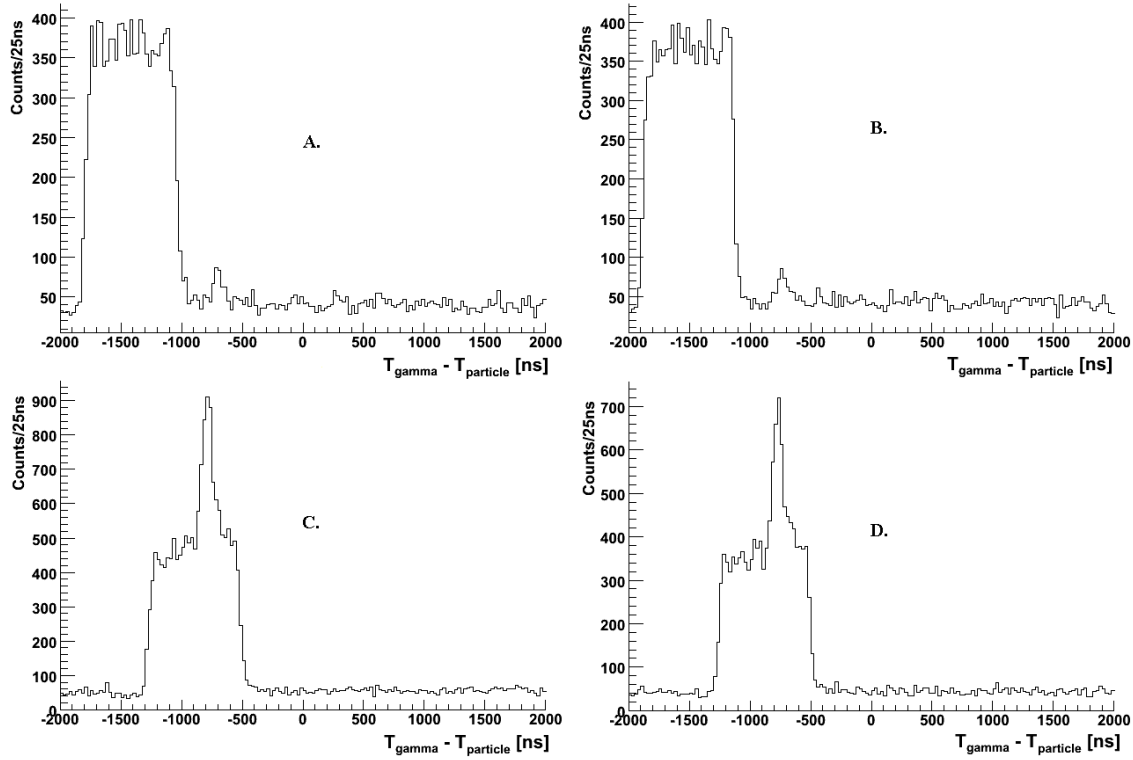


Figure 3.3 – Time difference between a gamma and a particle for each quadrant separately: A. quadrant 1 B. quadrant 2 C. quadrant 3 and D. quadrant 4. These timing spectra are for the ^{202}Po on ^{94}Mo reexperiment. The ^{202}Po on ^{104}Pd and the ^{206}Po on ^{104}Pd experiments show similar results.

already mentioned before that in a Coulomb-excitation event the projectile and target are emitted back-to-back in the center-of-mass frame, meaning that in a two-particle event projectile and target will be detected in opposite quadrants. Thus quadrant 1 and 3, and quadrant 2 and 4 cooperate for the two-particle events. Since the error in the downscaling occurred for quadrant 1 and 2, this implies that the contribution of the two-particle events to the prompt spectrum will be very small.

Figure 3.4 indicates the prompt window. The time window of $4\ \mu\text{s}$ is divided in a prompt window of 350 ns ($[-850; 500]$) and a random window of 3650 ns. The region between the red vertical lines in figure 3.4 is the prompt window and the rest of the time window is considered as the random window. The difference in length between the prompt and random window and the effect of the downscaling has been taken into account during further analysis of the gamma spectra.

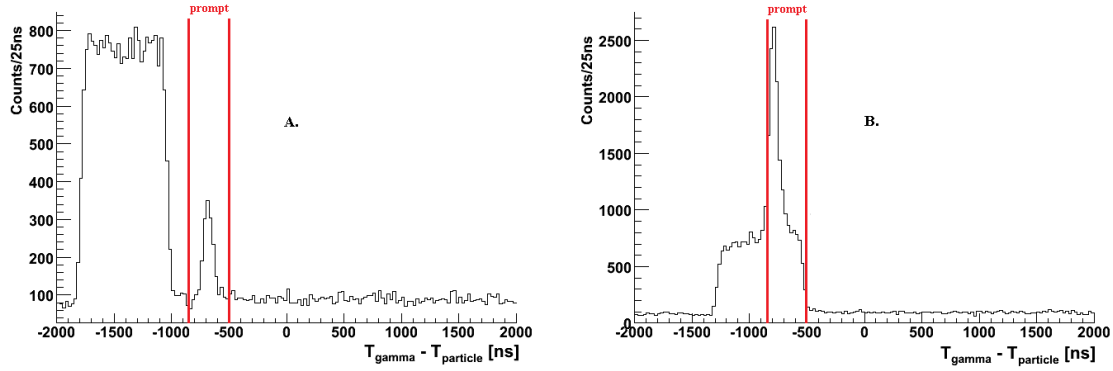


Figure 3.4 – Figure showing the prompt window for quadrant 1 and 4 for the ^{202}Po on ^{104}Pd experiment.

3.3 Analysis of the γ spectrum

3.3.1 ^{202}Po on ^{104}Pd experiment

Prompt and random spectrum

Using the previously defined prompt and random windows a prompt and random spectrum can be obtained. For the prompt spectrum, no condition was applied on the energy of the detected particle. Only γ rays with at least one prompt particle attached to it were selected and the corresponding γ spectrum is produced [vdW06]. The result of this selection is shown in figure 3.5. As can be seen from this spectrum several γ rays from the decay chain of ^{202}Po are present. The two broad bumps around 556 keV and 677 keV correspond to the deexcitation of the target and the projectile. The broadening of these peaks is caused by the Doppler shift and will be corrected for during further analysis.

Figure 3.6 shows the random gamma spectrum corresponding to the Coulomb-excitation events. The gamma transitions from the decay of ^{202}Po are observed. Also visible are two broad bumps, the same as seen in figure 3.5. These are actually Coulomb excitation events. The particles originating from the same event as the detected gamma ray are in this case not detected by the DSSSD and thus the gamma ray is coincident with one or two random particles. Further research on this phenomenon is still ongoing. This random spectrum is then subtracted from the prompt spectrum to filter out the background. As mentioned before the length of the prompt and random window is not the same. Therefore an appropriate scaling factor is needed when the subtraction is performed. In order to determine this scaling factor the number of counts of some intense beta decay lines is determined for the prompt and random spectrum. The ratio of these two numbers is then determined and a weighted subtraction factor (sf) is taken as a final number. The beta decay lines that are used in the calculation of the subtraction factor are indicated in both spectra by a $\bullet$. The result of this is shown in table 3.1. The number of counts over the energy range between 1.5 MeV and 3 MeV is also taken as this yields an average

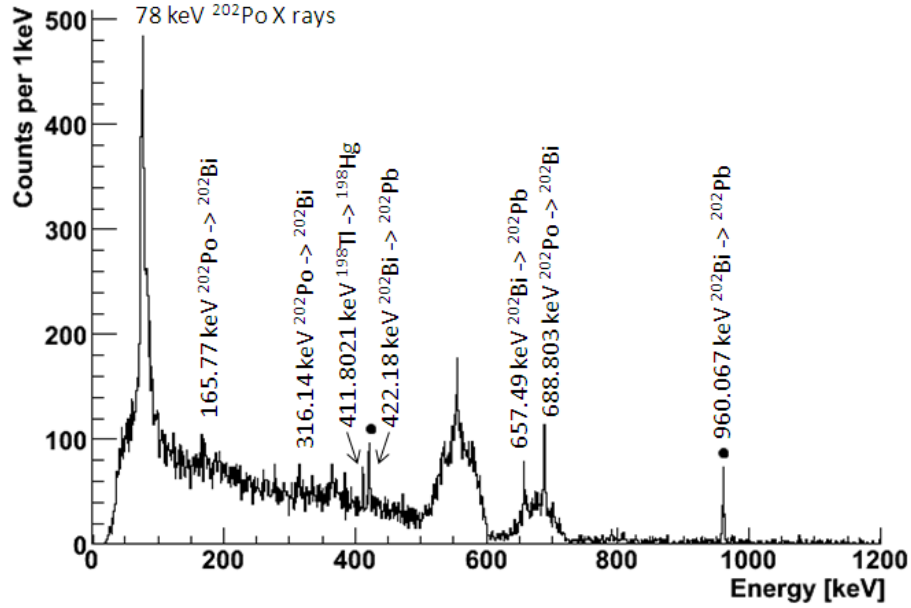


Figure 3.5 – Figure showing the prompt γ coincident spectrum corresponding to the Coulomb-excitation events. Two broad bumps are visible in the spectrum corresponding to the de-excitation of the target and projectile. Different γ transitions in the β^+ /EC decay of ^{202}Po and its daughters are also observed in this spectrum. Beta decay lines used in determining the subtraction factor are indicated with a $\bullet$.

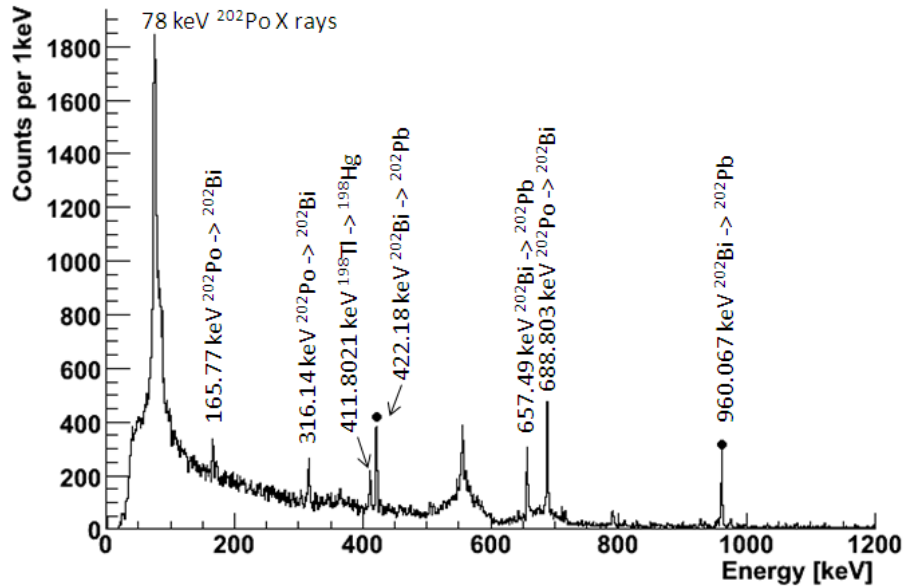


Figure 3.6 – Figure showing the random γ coincident spectrum corresponding to Coulomb-excitation events. Different γ transitions in the β^+ /EC decay of ^{202}Po and its daughters are also observed in this spectrum. Beta decay lines used in determining the subtraction factor are indicated with a $\bullet$.

subtraction factor. The background-subtracted spectrum that is obtained this way is shown in figure 3.7. Please note that for this spectrum the detection condition for the detected particles, as discussed in section 3.1, is applied as well. The deexcitation bumps coming from ^{202}Po and ^{104}Pd are still present as well as a large amount of polonium X

rays. The origin of these X rays will be investigated later on.

N_γ	E [keV]			
	422	959	1500-3000	
Prompt	112 (67)	124 (59)	229 (15)	
Random	841 (171)	783 (119)	1397 (37)	
sf	0.133 (84)	0.159 (73)	0.164 (12)	0.163 (11)

Table 3.1 – β -decay lines used to scale the random spectrum to the prompt spectrum. The last column corresponds to the number of counts over the full range 1.5 - 3 MeV. In bold is the weighted subtraction factor which is used to scale the random spectrum to the prompt. The large errors in some cases is due to statistics.

Doppler correction

The time it takes for the particle to travel the 26.5 mm from the target to the DSSSD is typically of the order of a few ns. The lifetime of the first excited state in ^{104}Pd , which can be populated by Coulomb excitation, is equal to 9.9 ps. This implies that the nuclei will γ decay in or right after the target. Thus the energy of the de-excitation gamma ray will be Doppler shifted as it is emitted in flight. This Doppler shift is clearly present in the prompt minus random gamma spectrum, see figure 3.7. The ^{202}Po de-excitation peak shows the same broadening, hence it can be expected that the lifetime of the first excited state in ^{202}Po is also of the order of ps. The Doppler shift is given by [War13]:

$$E_{LAB} = \frac{E_o}{\gamma(1 - \beta \cos(\zeta))} \quad (3.1)$$

E_{LAB} is the energy of the gamma ray in the laboratory frame, γ is the relativistic factor given by $1/\sqrt{1 - \beta^2}$, $\beta = v/c$ with v the velocity of the decaying nucleus, ζ is the angle between the nucleus and the emitted gamma ray and E_o is the energy of the gamma ray in the frame where the particle is at rest. If the de-exciting nucleus is detected in the DSSSD, ζ can be linked to the detection angles for the particle (θ_p, ϕ_p) and the detection angles for the gamma ray $(\theta_\gamma, \phi_\gamma)$ [War13]:

$$\cos(\zeta) = \sin(\theta_p) \sin(\theta_\gamma) \cos(\phi_p - \phi_\gamma) + \cos(\theta_p) \cos(\theta_\gamma) \quad (3.2)$$

with θ is the angle with respect to the beam axis and ϕ is the azimuthal angle. The relativistic factor β can be rewritten as:

$$\beta = \frac{v}{c} = \sqrt{\frac{2E_p}{m_p c^2}} = \sqrt{\frac{2E_p}{A \cdot 931.494}} \quad (3.3)$$

with E_p and m_p the energy and mass of the particle respectively and the factor 931.494 is the atomic mass unit expressed in MeV/c^2 . Equation 3.3 implies that the gamma spec-

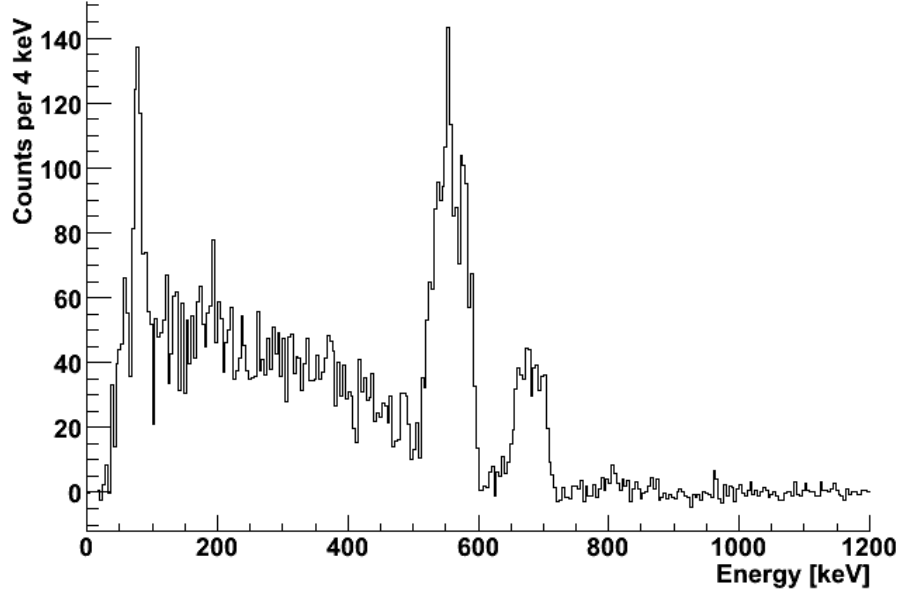


Figure 3.7 – This figure shows the prompt minus the properly scaled random gamma spectra for ^{202}Po on ^{104}Pd . This figure corresponds to the actual Coulomb-excitation events.

trum cannot be Doppler corrected for the target and projectile within the same spectrum [Kes10]. Figure 3.8 shows the effect of the Doppler correction on the random-subtracted gamma spectrum for the projectile.

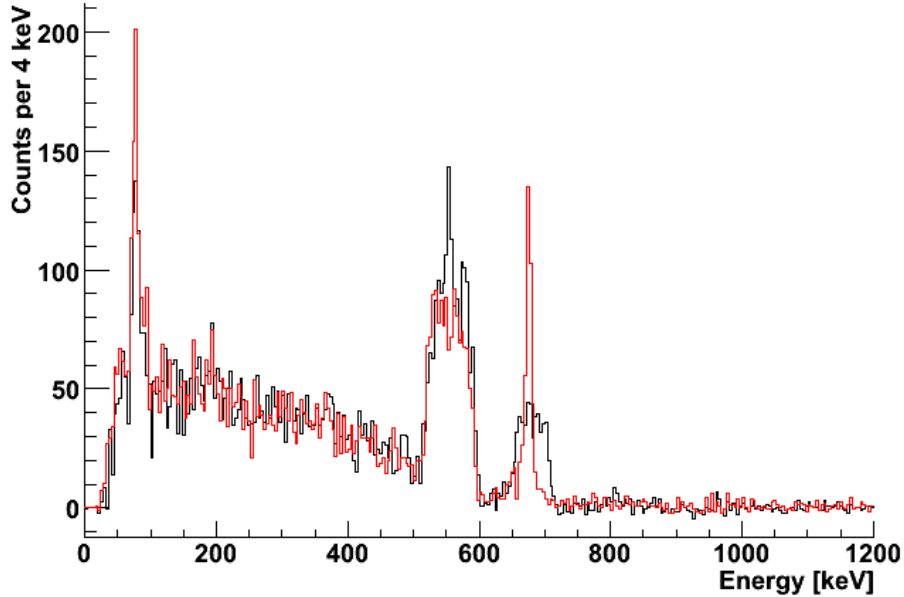


Figure 3.8 – Figure showing the effect of the Doppler correction on the random-subtracted gamma spectra. The red spectrum is obtained by applying the Doppler correction for the projectile. The random-subtracted gamma spectrum (black) is also shown for comparison. This is for the ^{202}Po on ^{104}Pd experiment.

The effect of the Doppler correction can clearly be seen from this spectrum. Using the Doppler correction the smeared out peak around 677 keV (representing the $2^+ \rightarrow 0^+$ transition) is transformed into a narrow peak with a Full Width at Half Maximum (FWHM) of 10 (2) keV. This spectrum also shows that there is a large amount of X rays present (peak around 78 keV). The origin of these X rays is discussed in section 3.4. The same Doppler correction can also be performed for the target, the result of which is shown in figure 3.9. As can be seen in figure 3.9, the de-excitation peak around 556 keV, representing the $2^+ \rightarrow 0^+$ transition of ^{104}Pd , becomes a narrow peak with a FWHM of 7.6 (7) keV.

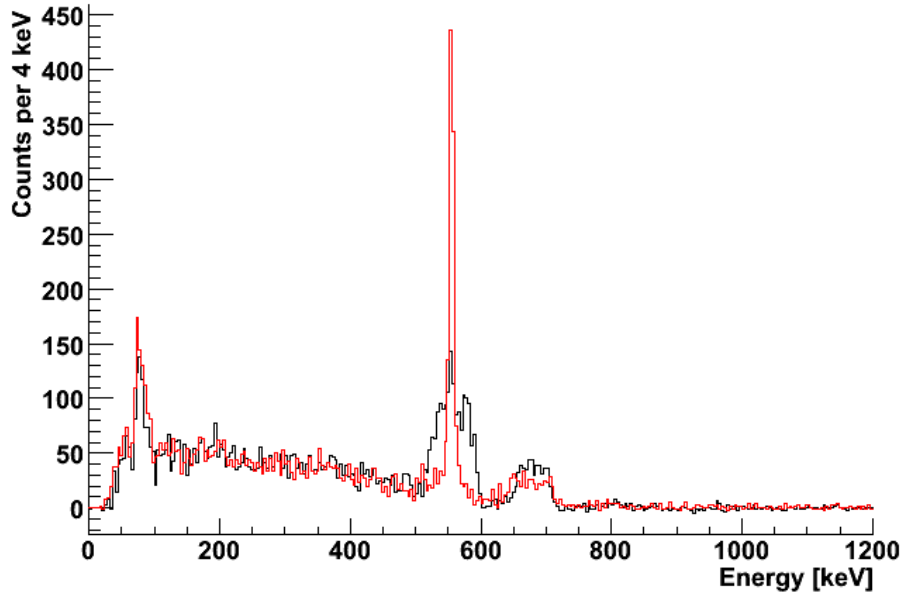


Figure 3.9 – Figure showing the effect of the Doppler correction on the random-subtracted gamma spectra. The red spectrum is obtained by applying the Doppler correction for the target. The random-subtracted gamma spectrum (black) is also shown for comparison. This is for the ^{202}Po on ^{104}Pd experiment.

Integration of the de-excitation peaks

In order to extract information about the $B(E2, 0^+ \rightarrow 2^+)$ value and the quadrupole moment of the first excited state of ^{202}Po , the number of counts in the de-excitation γ peaks need to be determined. Using equation 1.29 it is then possible to determine the relative cross section for Coulomb excitation when comparing projectile and target excitation. Using this information the $B(E2, 0^+ \rightarrow 2^+)$ can be extracted. The $2^+ \rightarrow 0^+$ photo peaks in the Doppler-corrected and random-subtracted spectra for projectile and target are fitted with a Gaussian function with linear background to obtain the counts in these peaks. The integration has been performed on three angular ranges of the DSSSD. By dividing the angular range of the DSSSD into a number of ranges a gain in sensitivity on the second-order effect of the diagonal matrix element on the Coulomb excitation cross section is achieved. In this case the 12 outer strips of the DSSSD were used. The 4 most inner strips of the DSSSD were not used due to overlap of the projectile and target

kinematics in this range making it impossible to separate the target and projectile nucleus from each other. The laboratory angles covered by the 12 most outer strips of the DSSSD range from 32.7° to 57.1° . Since only a limited range of the DSSSD is used during the analysis, statistics will be slightly reduced. These 12 strips were divided in three groups of 4 strips for the division in angular ranges. Table 3.2 shows the result of this procedure.

Angular Range (LAB)	677 keV	556 keV
$32.7^\circ - 43.2^\circ$	153 (53)	407 (71)
$43.3^\circ - 51.1^\circ$	111 (45)	332 (70)
$51.2^\circ - 57.1^\circ$	74 (34)	198 (67)
Total	338 (79)	937 (120)

Table 3.2 – This table shows the integrals of the $2^+ \rightarrow 0^+$ photo peaks of the projectile and target for the three angular ranges. The angular ranges are denoted in the laboratory frame. The 677 keV peak corresponds to the de-excitation of ^{202}Po and the 556 keV peak corresponds to the de-excitation of ^{104}Pd . These numbers are not corrected for the efficiency of the γ detection.

The observed peaks in the prompt minus random Doppler-corrected spectrum for the projectile can also be compared to the transitions previously observed in the β^+/EC -decay study of ^{202}Po (figure 2.23). Only the 2^+ state at 677.20 keV has been populated during this experiment since the $2^+ \rightarrow 0^+$ transition is observed. Since no other transition is observed no conclusion could be drawn about the population of the other levels. But this could be a result of the low statistics linked to the downscaling problem and their high excitation energy. However it is possible to determine an upper limit on the number of counts in these peaks. The method employed in calculating these upper limits is discussed in the paper of Helene et al. [Hel83]. In determining these upper limits, a 2σ confidence level was used indicating that there is a 95% probability that the number of counts in the peak is lower than the upper limit. The upper limit for the 625.3 keV gamma, related to the $2_2^+ \rightarrow 0_1^+$ transition, yields a value of 19 counts. The upper limit for the 571.3 keV gamma, related to the $4_1^+ \rightarrow 2_1^+$ transition, yields a value of 263 counts. Please note that the 571.3 keV gamma lies in the palladium peak complicating the upper limit determination.

3.3.2 ^{202}Po on ^{94}Mo experiment

Prompt and random spectrum

The data of the ^{202}Po on ^{94}Mo experiment is analyzed using the same method as for the ^{202}Po on ^{104}Pd experiment. Figure 3.10 shows the prompt gamma coincidence spectrum. Several γ rays from the decay chain of ^{202}Po are present. One broad bump around 677 keV, corresponding to the de-excitation of the projectile, is clearly visible. A broad de-excitation bump around 871 keV coming from the target is not clearly visible in this spectrum. This is due to the low statistics for the target excitation. The broadening

of these peaks is caused by the Doppler shift and will be corrected for during further analysis.

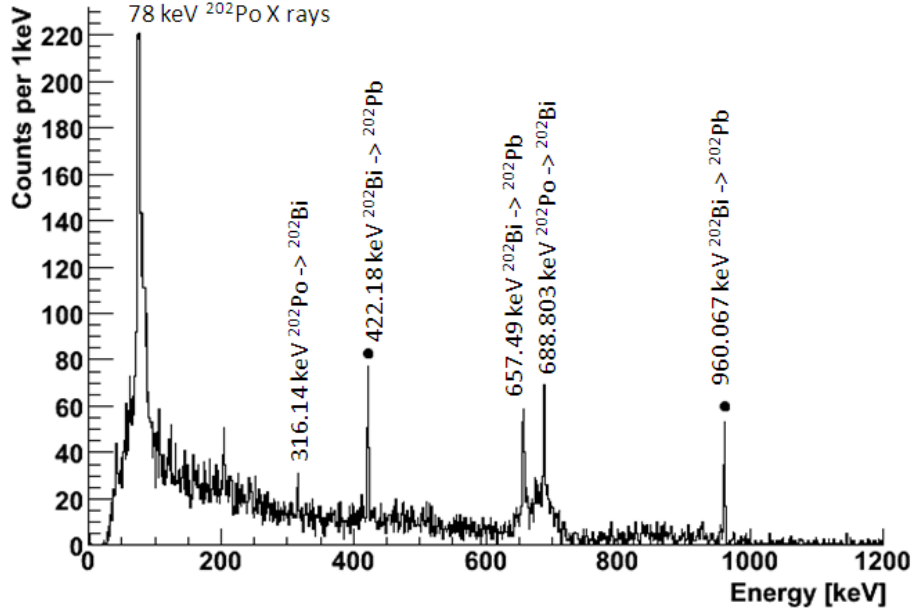


Figure 3.10 – Figure showing the prompt γ coincident spectrum corresponding to the Coulomb-excitation events. Two broad bumps are visible in the spectrum corresponding to the de-excitation of the target and projectile. Different γ transitions in the β^+ /EC decay of ^{202}Po and its daughters are also observed in this spectrum. Beta decay lines used in determining the subtraction factor are indicated with a $\bullet$.

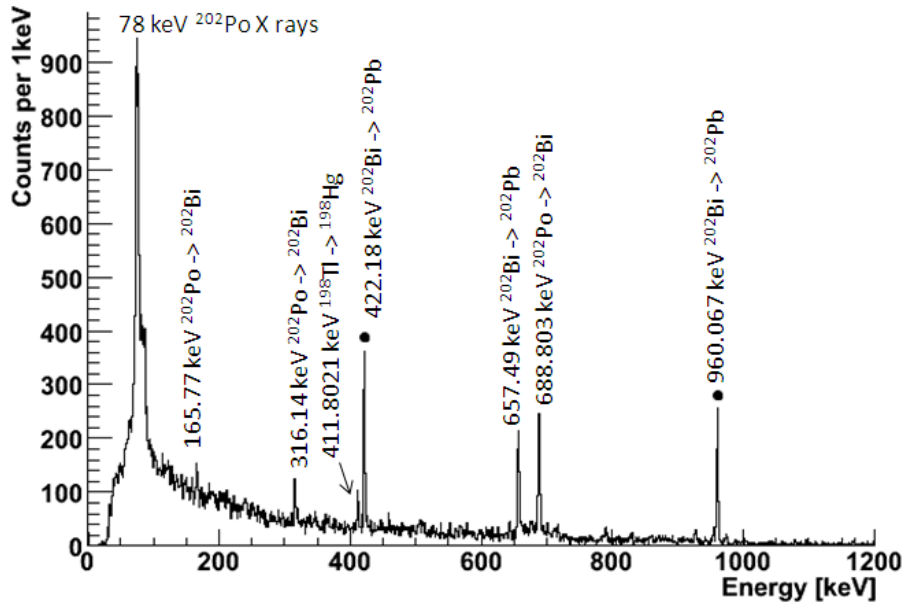


Figure 3.11 – Figure showing the random γ coincident spectrum corresponding to Coulomb-excitation events. Different γ transitions in the β^+ /EC decay of ^{202}Po and its daughters are also observed in this spectrum. Beta decay lines used in determining the subtraction factor are indicated with a $\bullet$.

Figure 3.11 shows the random gamma spectrum corresponding to the Coulomb-excitation events. The gamma transitions from the decay of ^{202}Po are observed and again the broad bump, also seen in figure 3.10, is observed due to reason explained before. This random spectrum is then subtracted from the prompt spectrum, by means of a subtraction factor, to filter out the background. Using some intense beta decay lines, indicated by a $\bullet$ in both spectra, a subtraction factor is determined. The result is shown in table 3.3.

N_γ	E [keV]			
	422	959	1500-3000	
Prompt	137 (64)	113 (39)	188 (14)	
Random	816 (155)	842 (112)	1115 (33)	
sf	0.168 (84)	0.134 (49)	0.169 (13)	0.166 (13)

Table 3.3 – β -decay lines used to scale the random spectrum to the prompt spectrum. The last column corresponds to the number of counts over the full range 1.5 - 3 MeV. In bold is the average subtraction factor which is used to scale the random spectrum to the prompt. The large errors in some cases is due to statistics.

The background-subtracted spectrum obtained is shown in figure 3.12. Please note that for this spectrum the detection condition for the detected particles, as discussed in section 3.1, is applied as well. As can be observed from this spectrum is that the de-excitation bump coming from the target is now visible but very shallow. This will result in low statistics for target de-excitation. The de-excitation bump coming from ^{202}Po is still present as well as a large amount of Polonium X rays. The origin of these X rays will be investigated later on.

Doppler correction

The time it takes for the particle to travel the 26.5 mm from the target to the DSSSD is typically of the order of a few ns. The lifetime of the first excited state in ^{94}Mo , which can be populated by Coulomb excitation, is equal to 2.77 ps. This will result in a Doppler shift of the energy of the de-excitation gamma ray (as explained before). This Doppler shift is also present for gamma rays coming from the ^{202}Po nucleus. A Doppler correction is again performed for the projectile and target separately. The effect of the Doppler correction for the projectile is shown in figure 3.13.

The effect of the Doppler correction can clearly be seen from this spectrum. Using the Doppler correction the smeared out peak around 677 keV (representing the $2^+ \rightarrow 0^+$ transition) is transformed into a narrow peak with a FWHM of 9 (2). The spectrum also show that there is a large amount of X rays present (peak around 78 keV). The origin of these X rays is discussed in section 3.4. The same Doppler correction can thus also be performed for the target, the result of which is shown in figure 3.14.

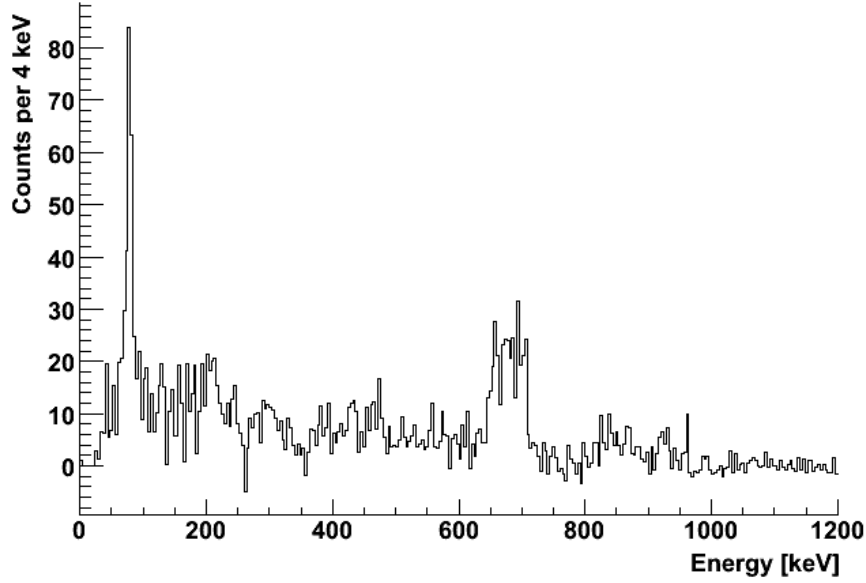


Figure 3.12 – This figure shows the prompt minus the properly scaled random gamma spectra for ^{202}Po on ^{94}Mo . This figure corresponds to the actual Coulomb-excitation events.

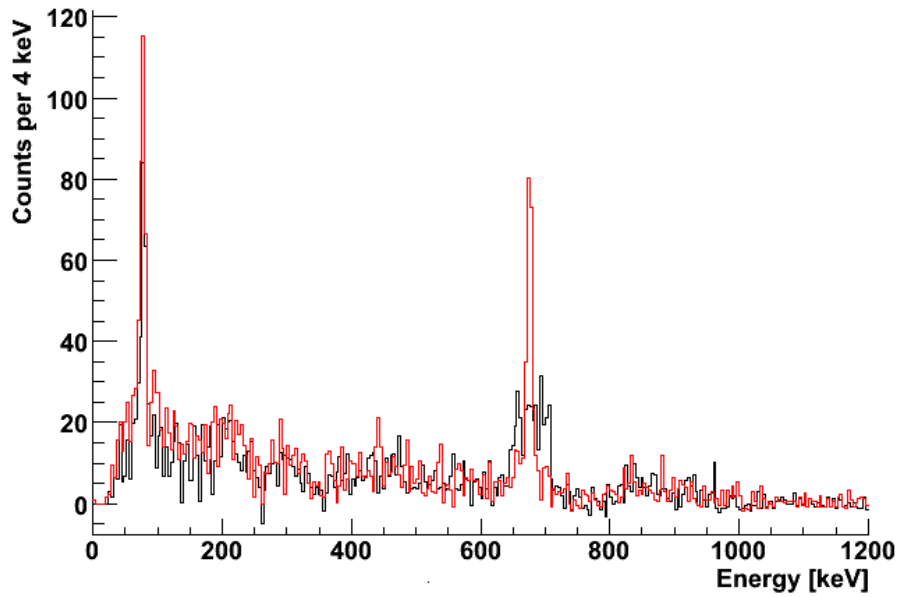


Figure 3.13 – Figure showing the effect of the Doppler correction on the random-subtracted gamma spectra. The red spectrum is obtained by applying the Doppler correction for the projectile. The random-subtracted gamma spectrum (black) is also shown for comparison. This is for the ^{202}Po on ^{94}Mo experiment.

Figure 3.14 is a perfect example of the importance of the Doppler correction. The de-excitation peak around 871 keV, representing the $2^+ \rightarrow 0^+$ transition of ^{94}Mo , becomes clearly visible when Doppler correction is applied whereas it was barely visible in the random-subtracted gamma spectrum. The FWHM of this peak is 17 (5) keV. This value is not as low as the others but this is due to the very low statistics of this run and more importantly due to the lower Coulomb excitation probability of ^{94}Mo . Also visible is the

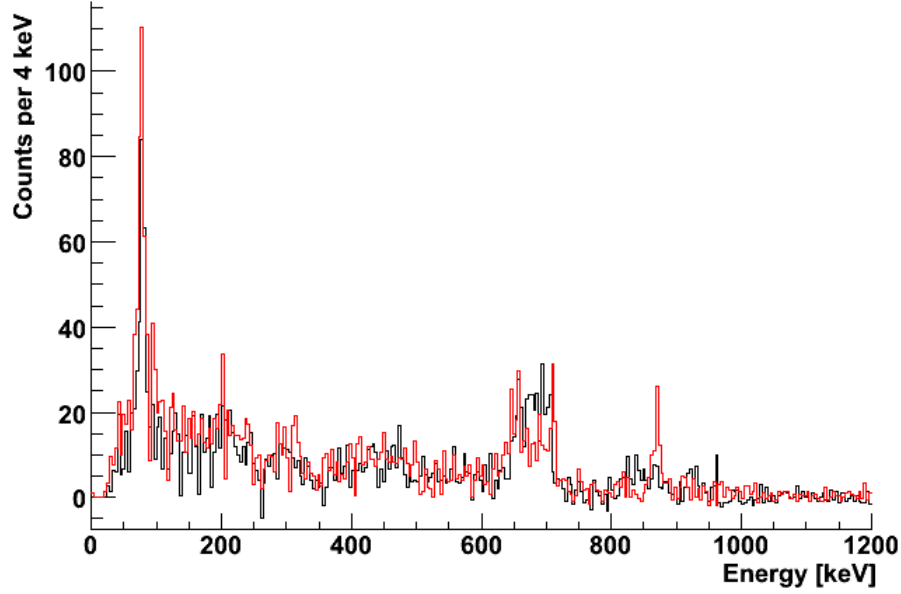


Figure 3.14 – Figure showing the effect of the Doppler correction on the random-subtracted gamma spectra. The red spectrum is obtained by applying the Doppler correction for the target. The random-subtracted gamma spectrum (black) is also shown for comparison. This is for the ^{202}Po on ^{94}Mo experiment.

small peak around 204 keV. The origin of this peak was investigated and it was concluded that this peak is the result of Coulomb excitation of ^{95}Mo . This indicates that a small amount of contamination was present in the molybdenum target.

Integration of the de-excitation peaks

The integration of the de-excitation peaks was performed using the same procedure as explained for the ^{202}Po on ^{104}Pd experiment. Again only the 12 outer strips of the DSSSD were used. These 12 strips were divided in three groups of 4 strips for the division in angular ranges. Table 3.4 shows the result of this procedure.

Angular Range (LAB)	677 keV	871 keV
32.7° - 43.2°	92 (41)	28 (23)
43.3° - 51.1°	71 (39)	29 (21)
51.2° - 57.1°	44 (33)	14 (13)
Total	207 (66)	71 (34)

Table 3.4 – This table shows the integrals of the $2^+ \rightarrow 0^+$ photo peaks of the projectile and target for the three angular ranges. The angular ranges are denoted in the laboratory frame. The 677 keV peak corresponds to the de-excitation of ^{202}Po and the 871 keV peak corresponds to the de-excitation of ^{94}Mo . These numbers are not corrected for the efficiency of the γ detection.

The observed peaks in the prompt minus random Doppler-corrected spectrum for the projectile can also be compared to the transitions previously observed in the β /EC-decay study of ^{202}Po (figure 2.23). Only the 2^+ state at 677.20 keV has been populated during this experiment since the $2^+ \rightarrow 0^+$ transition is observed. Since no other transition is observed no conclusion could be drawn about the population of the other levels. However in the same way as before, an upper limit on the number of counts can be determined. The upper limit for the 571.3 keV gamma, related to the $4_1^+ \rightarrow 2_1^+$ transition, yields a value of 21 counts (2σ confidence level). The upper limit for the 625.3 keV gamma, related to the $2_2^+ \rightarrow 0_1^+$ transition, could not be determined for this experiment. Table 3.4 shows that the statistics for target excitation is very low. But by combining the result of the two ^{202}Po experiments, the effect of the low statistics can be circumvented.

3.3.3 ^{206}Po on ^{104}Pd experiment

Prompt and random spectrum

The data of the ^{206}Po on ^{104}Pd experiment is analyzed using the same method as for the ^{202}Po on ^{104}Pd experiment. Figure 3.15 shows the prompt gamma coincidence spectrum. Several γ rays from the decay chain of ^{202}Po are present. These are residual isotopes still present in the collision chamber after the ^{202}Po experiments. Two broad bumps, one around 701 keV and one around 556 keV, are clearly visible. They correspond to the de-excitation of the projectile and target respectively. The broadening of these peaks is caused by the Doppler shift and will be corrected for during further analysis.

Figure 3.16 shows the random coincidence gamma spectrum corresponding to the Coulomb-excitation events. The gamma transitions from the decay of ^{206}Po are also observed together with the two broad bumps, the same as in figure 3.15, due to reasons explained before. This random spectrum is then subtracted from the prompt spectrum, by means of a subtraction factor, to filter out the background. Using some intense beta decay lines, indicated by a $\bullet$ in both spectra, a subtraction factor is determined. The result is shown in table 3.5. The obtained subtraction factor deviates strongly from the other experiments. As of yet this deviation remains unexplained. A possible explanation could be the large difference in beam intensity observed between the ^{206}Po experiment and the ^{202}Po experiments. The intensity of the ^{206}Po beam yielded a value of $2 \cdot 10^5$ pps while the intensity of the ^{202}Po beam was $7 \cdot 10^5$ pps and $4 \cdot 10^5$ pps for the ^{202}Po on ^{104}Pd experiment and the ^{202}Po on ^{94}Mo experiment respectively.

The background-subtracted spectrum obtained is shown in figure 3.17. Please note that for this spectrum the detection condition for the detected particles, as discussed in section 3.1, is applied as well. The de-excitation bumps coming from ^{202}Po and ^{104}Pd are still present as well as a large amount of polonium X rays, however to a lesser extent as in the ^{202}Po on ^{104}Pd experiment. The origin of these X rays will be investigated later on.

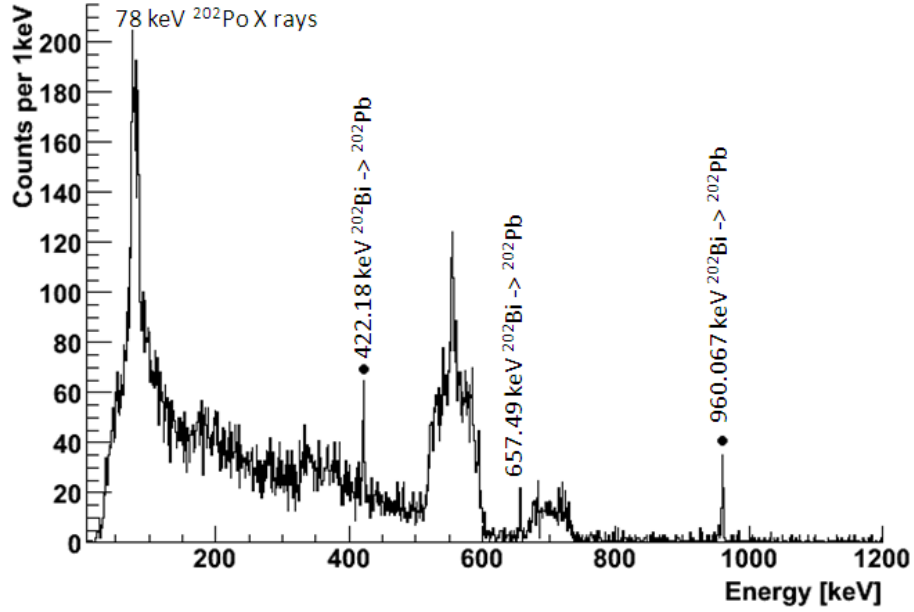


Figure 3.15 – Figure showing the prompt γ coincident spectrum corresponding to the Coulomb-excitation events. Two broad bumps are visible in the spectrum corresponding to the de-excitation of the target and projectile. Different γ transitions in the β^+ /EC decay of ^{206}Po and its daughters are also observed in this spectrum. Beta decay lines used in determining the subtraction factor are indicated with a $\bullet$.

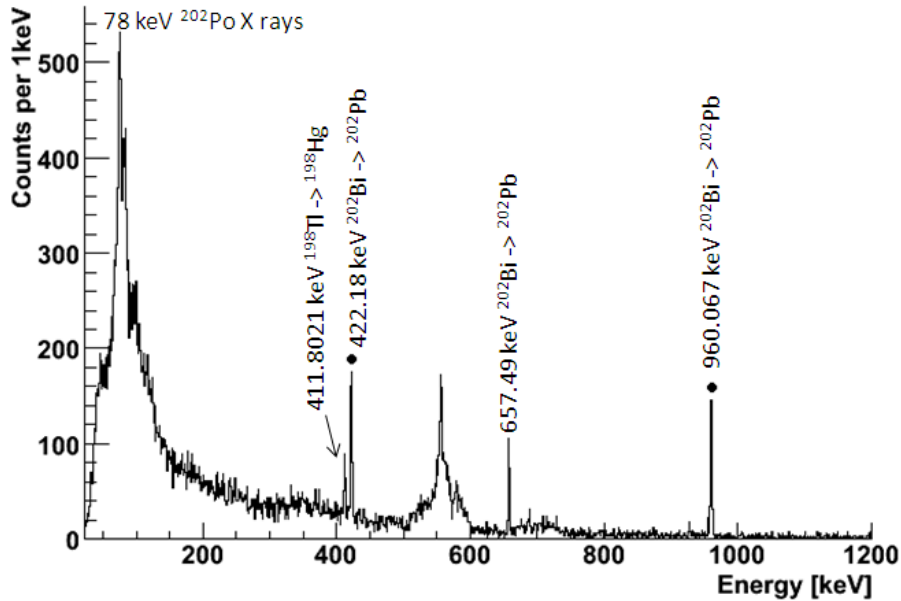


Figure 3.16 – Figure showing the random γ coincident spectrum corresponding to Coulomb-excitation events. Different γ transitions in the β^+ /EC decay of ^{206}Po and its daughters are also observed in this spectrum. Beta decay lines used in determining the subtraction factor are indicated with a $\bullet$.

Doppler correction

The time it takes for the particle to travel the 26.5 mm from the target to the DSSSD is typically of the order of a few ns. The lifetime of the first excited state in ^{104}Pd , which

N_γ	E [keV]			
	422	959	1500-3000	
Prompt	102 (59)	78 (46)	164 (13)	
Random	399 (111)	409 (81)	613 (25)	
sf	0.25 (16)	0.19 (12)	0.27 (2)	0.26 (2)

Table 3.5 – β -decay lines used to scale the random spectrum to the prompt spectrum. The last column corresponds to the number of counts over the full range 1.5 - 3 MeV. In bold is the average subtraction factor which is used to scale the random spectrum to the prompt. The large errors in some cases is due to statistics.

can be populated by Coulomb excitation, is equal to 9.9 ps. This will result in a Doppler shift of the energy of the de-excitation gamma ray (as explained before). This Doppler shift is also present for gamma rays coming from the ^{202}Po nucleus. A Doppler correction is again performed for the projectile and target separately. The effect of the Doppler correction for the projectile is shown in figure 3.18.

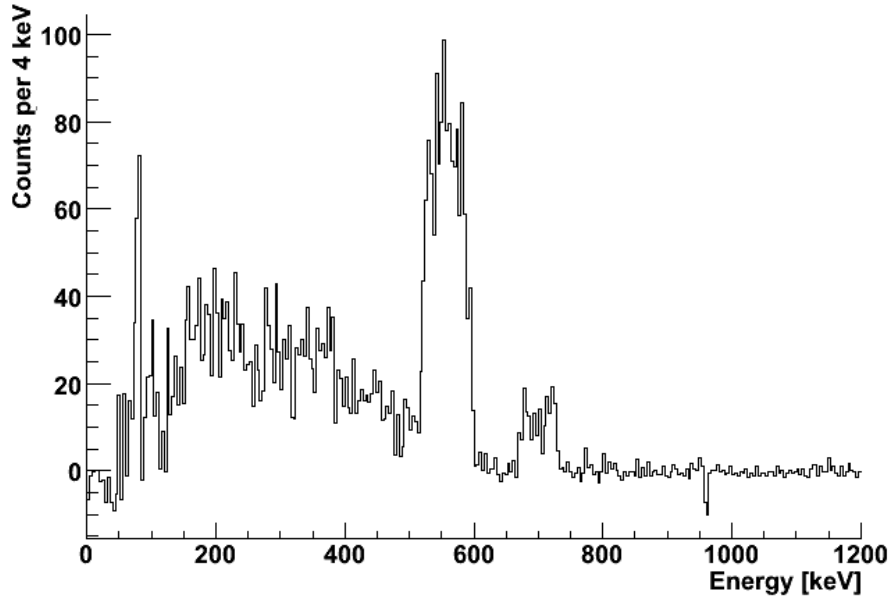


Figure 3.17 – This figure shows the prompt minus the properly scaled random gamma spectra for ^{206}Po on ^{104}Pd . This figure corresponds to the actual Coulomb- excitation events.

Using the Doppler correction the smeared out peak around 701 keV (representing the $2^+ \rightarrow 0^+$ transition) is transformed into a narrow peak with a FWHM of 9 (2) keV. This spectrum also shows that there is a large amount of X rays present (peak around 78 keV). The origin of these X rays is discussed in section 3.4. The same Doppler correction can thus also be performed for the target, the result of which is shown in figure 3.19. As can be seen in figure 3.19, the de-excitation peak around 556 keV, representing the $2^+ \rightarrow 0^+$ transition of ^{104}Pd , becomes a narrow peak with a FWHM of 8.5 (8) keV.

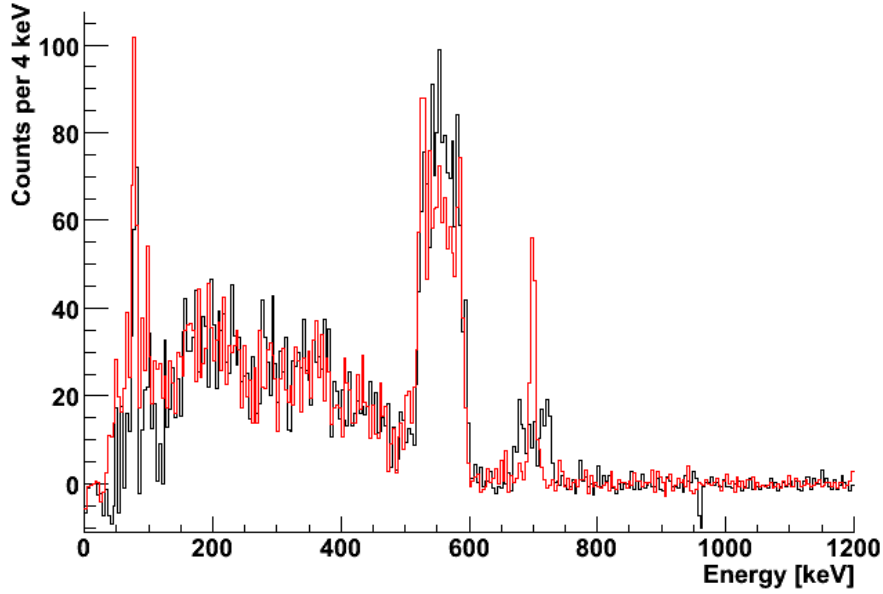


Figure 3.18 – Figure showing the effect of the doppler corrected random-subtracted gamma spectra for the projectile (red) compared with the random-subtracted gamma spectrum (black). This is for the ^{206}Po on ^{104}Pd run.

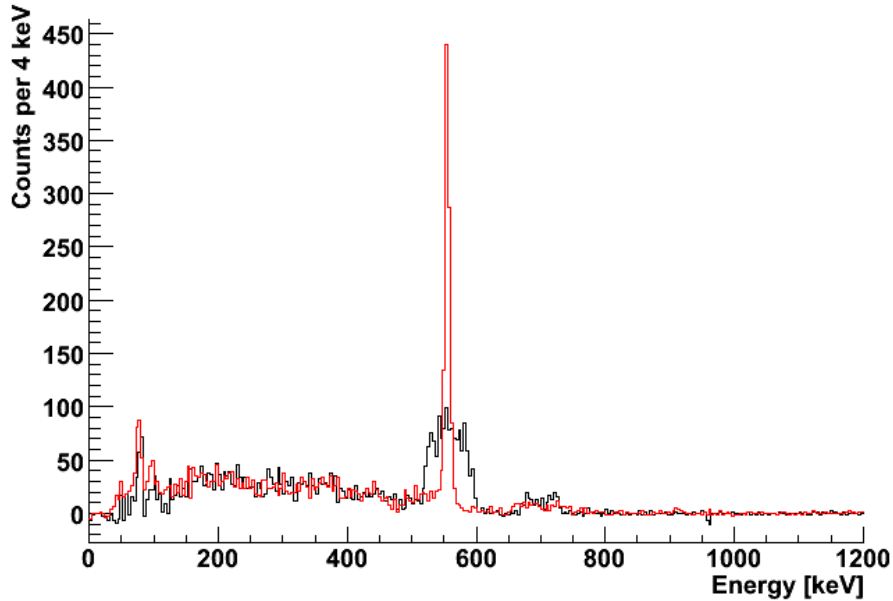


Figure 3.19 – Figure showing the effect of the doppler corrected random-subtracted gamma spectra for the target (red) compared with the random-subtracted gamma spectrum (black). This is for the ^{202}Po on ^{104}Pd run.

Integration of the de-excitation peaks

The analysis of this experiment was solely done in order to investigate the origin of the X rays. Therefore there is no need to extract information about the $B(E2, 0^+ \rightarrow 2^+)$ value of ^{206}Po . However in order to be able to determine the flux of incoming Po nuclei, the counts in the de-excitation γ peak of the palladium nucleus needs to be determined.

The integration of the de-excitation peaks was performed using the same procedure as explained for the ^{202}Po on ^{104}Pd experiment. Again only the 12 outer strips of the DSSSD were used. These 12 strips were divided in three groups of 4 strips for the division in angular ranges. Table 3.6 shows the result of this procedure.

Angular Range (LAB)	701 keV	556 keV
32.7° - 43.2°	66 (29)	376 (90)
43.3° - 51.1°	40 (21)	325 (73)
51.2° - 57.1°	31 (19)	211 (60)
Total	137 (41)	912 (130)

Table 3.6 – This table shows the integrals of the $2^+ \rightarrow 0^+$ photo peaks of the projectile and target for the three angular ranges. The angular ranges are denoted in the laboratory frame. The 701 keV peak corresponds to the de-excitation of ^{206}Po and the 556 keV peak corresponds to the de-excitation of ^{104}Pd . These numbers are not corrected for the efficiency of the γ detection.

The observed peaks in the prompt minus random Doppler-corrected spectrum for the projectile can also be compared to the transitions previously observed in the β/EC -decay study of ^{206}Po (figure 2.23). Only the 2^+ state at 700.66 keV has been populated during this experiment since the $2^+ \rightarrow 0^+$ transition is observed. Since no other transition is observed no conclusion could be drawn about the population of the other levels. However in the same way as before, an upper limit on the number of counts can be determined. The upper limit for the 461.5 keV gamma, related to the $2_2^+ \rightarrow 2_1^+$ transition, yields a value of 26 counts (2σ confidence level). The upper limit for the 1162.2 keV gamma, related to the $2_2^+ \rightarrow 0_1^+$ transition, could not be determined for this experiment due to the lack of counts in this region.

3.4 X-ray analysis

As mentioned before, the random-subtracted projectile Doppler-corrected spectra contain a large amount of X rays. In this section the origin of these X rays is further investigated. Fitting the X-ray peak proved to be too difficult since the background could not be reproduced to a reasonably standard by applying a fit. Therefore the integrated number of counts in a region around the X-ray peak was determined instead. The entire γ spectrum was then simulated and the background around the X-ray peak was extracted using the simulated spectrum. The background counts were then subtracted from the integral over the specified region resulting in the number of X-ray counts. This process will now be explained in more detail.

3.4.1 GÉANT4 simulations

As mentioned in the introduction of this section, the γ spectrum was simulated in order to extract the background of the X-ray peak. The simulation were performed using the GÉANT4 simulation toolkit. For more information about the GÉANT4 simulation toolkit see [Ago03]. GÉANT4 includes a number of experimental characteristics like target thickness, density of the target, molar mass of the target, mass number of the projectile, etc... An important property of the GÉANT simulation toolkit is that the description of the entire experimental setup, meaning DSSSD and the γ detector, are included. However, when conducting the simulation only the γ detector setup was taken into account. The populated states and the energy of the X-ray peak were included in the simulation along with their population percentages. In the previous section the number of counts in the de-excitation peak of target and projectile was already determined. When determining their population percentages, the ratio of these percentages is set equal to the ratio of the counts in their respective peaks. The only variable is then the population percentage of the X-ray peak. This percentage is then allowed to vary while keeping the ratio of the population percentages of the de-excitation peaks constant. The number of simulated events is then varied as to get the best overlap with the experimental spectrum. The result of this process is shown in figure 3.20. In all three experiments a clear peak around 78 keV was present representing K_α X rays. Only in the ^{202}Po on ^{104}Pd experiment, the presence of K_β X rays was clearly visible. Nonetheless, during the simulation K_β X rays were included for all three experiments.

When assessing the simulated spectra a good overlap of the Compton part of the spectra is desired as well as a good overlap with the X-ray peak. Since GÉANT4 was never designed for Coulomb excitation experiments the Doppler effect creates artifacts in the simulated spectra resulting in two peaks with the center between these two peaks corresponding to the de-excitation energy of the target or projectile. The X-ray peak of the simulated spectra is then fitted with a Gaussian function with a linear background and the linear background parameters are extracted. The results are summarized in table 3.7. These parameters will be used to calculate the number of X rays in the background.

Target	Projectile	Gain	Offset
^{104}Pd	^{202}Po	0.158 (24)	30.0 (16)
^{94}Mo	^{202}Po	0.053 (14)	12 (2)
^{104}Pd	^{206}Po	0.0594 (72)	15.42 (72)

Table 3.7 – Table showing the gain and offset extracted from the simulated spectra for the three experiments. Note that these values correspond to a binsize = 4. In order to correct for the binning, divide both numbers by the size of the bins.

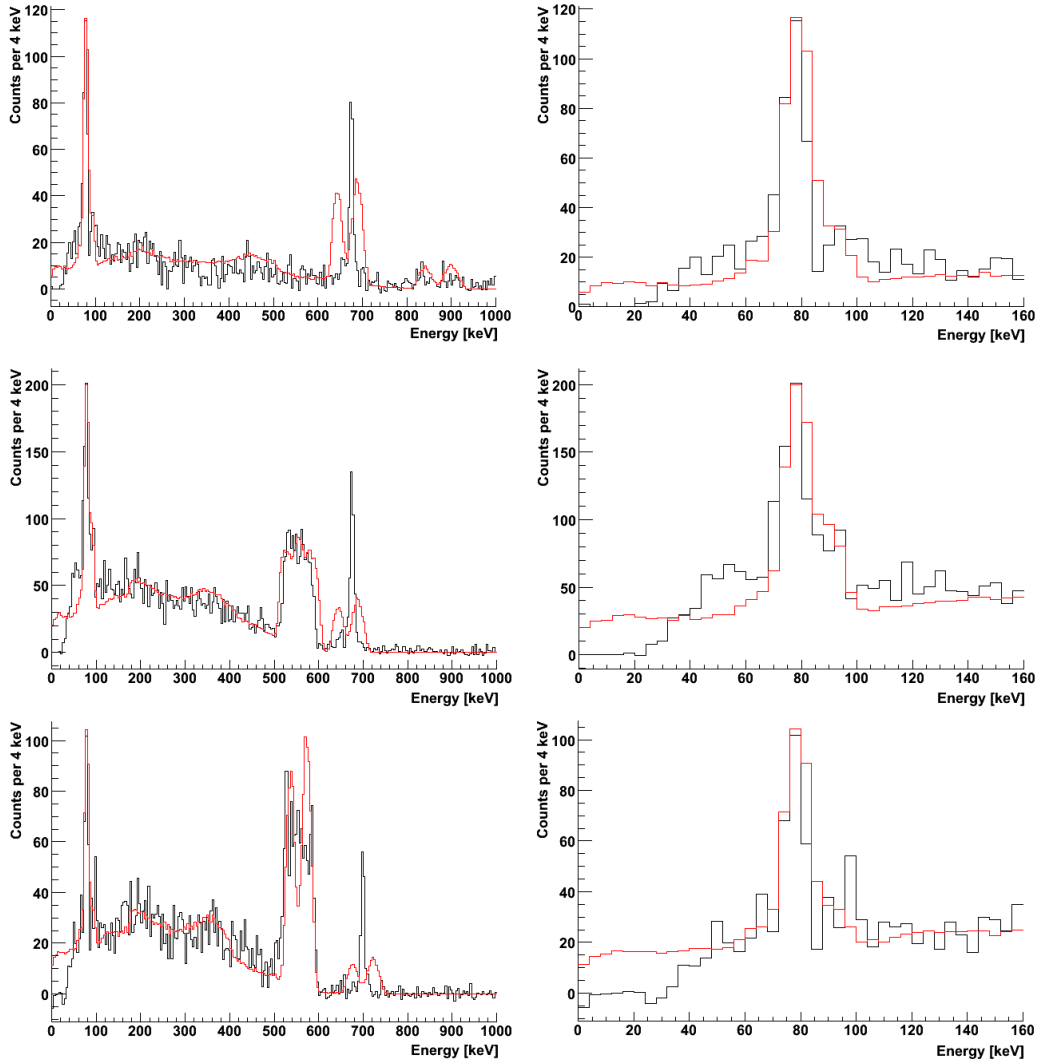


Figure 3.20 – This figure shows the comparison between the experimental spectra (black) and simulated spectra (red). The right column shows a zoom on the X rays. Top row: ^{202}Po on ^{94}Mo experiment. Center row: ^{202}Po on ^{104}Pd experiment. Bottom row: ^{206}Po on ^{104}Pd experiment.

3.4.2 X rays detected

Figure 3.21 shows a zoom of the region around the X ray peak for all three experiments. The region over which the integration is performed is depicted in green and ranges from 55 keV to 100 keV. The error on this number was calculated by considering that the spectrum consists of the subtraction of the prompt spectra, containing 1-particle prompt events and 2-particle prompt events, and the random spectra, containing 1-particle random events and 2-particle random events. The total amount of counts in these four spectra was then extracted using the same integration window. The error on the prompt minus random spectrum then equals $\sqrt{p + sf^2 * r}$ with p the number of counts in the prompt spectra, r the number of counts in the random spectra and sf is the subtraction factor. The total amount of X rays in the background can then be extracted by integrating the linear background over the same range. This number is then subtracted from the total amount

of X-ray counts and thus the amount of detected X rays is obtained.

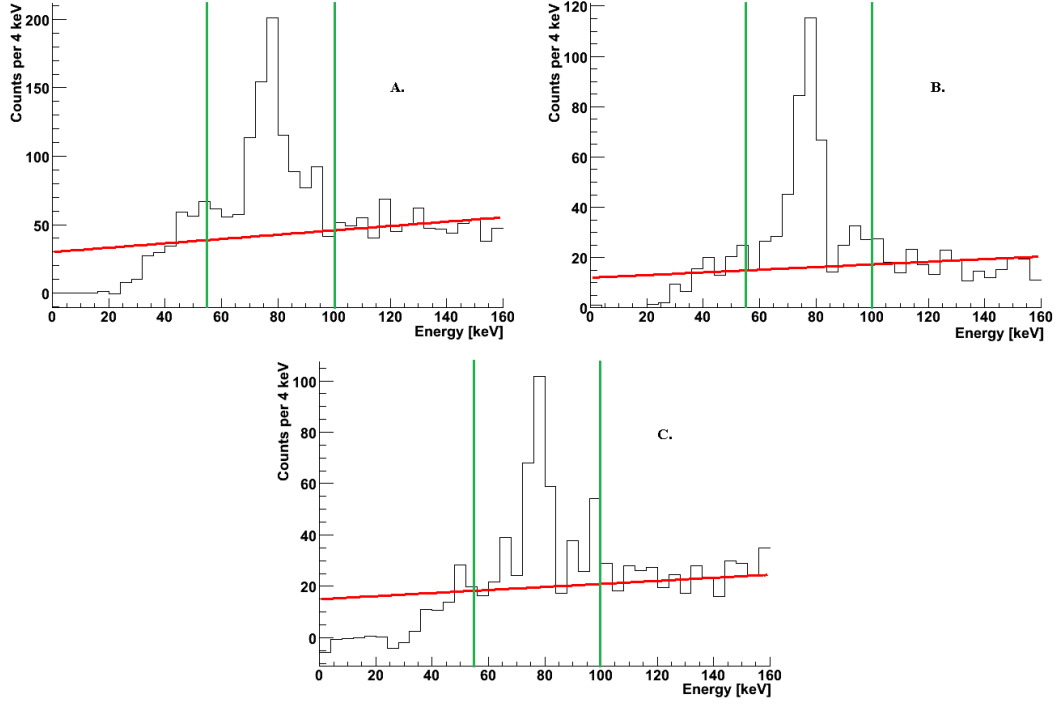


Figure 3.21 – Zoom on the region around the X ray peak. The linear background extracted from the simulation is shown in red. The integration interval is shown in green. A. ^{202}Po on ^{104}Pd experiment. B. ^{202}Po on ^{94}Mo experiment. C. ^{206}Po on ^{104}Pd experiment.

The detected amount of X rays can then be compared to the theoretically expected amount. As mentioned in section 1.3.5, X rays can originate from conversions and from collisions between projectile and target. Using the counts in the projectile de-excitation peaks and the known conversion coefficients the amount of X rays related to conversions can be calculated and using formula 1.33 the amount of X rays induced by collisions can be calculated. Table 3.8 summarizes the results and allows a comparison between the estimated amount of X rays and the detected amount of X rays.

Target	Projectile	Total	Bkg	Detected	X_{coll}	X_{con}	Rest
^{104}Pd	^{202}Po	994 (46)	476 (50)	518 (68)	90 (19)	7 (2)	421 (71)
^{94}Mo	^{202}Po	428 (34)	181 (49)	246 (60)	50 (21)	4 (2)	192 (64)
^{104}Pd	^{206}Po	395 (36)	225 (23)	169 (43)	82 (18)	3 (1)	84 (47)

Table 3.8 – Result of the X-ray analysis. Total: total amount of counts in the interval 55 keV to 100 keV, Bkg: amount of background counts, Detected: background subtracted amount of X rays, X_{coll} : X rays originating from collisions, X_{con} : X rays originating from conversion, Rest: remaining amount of X rays. Note that the detection efficiency of the X rays is taken into account.

As can be seen from table 3.8 a large amount of remaining X rays cannot be accounted for. A first possible origin of these X rays lies in the E0 transition from the 0_2^+ state to

the ground state in ^{202}Po already observed by [Bij98]. The 0_2^+ state can be populated by a two-step Coulomb excitation via the first excited 2^+ state. The 0_2^+ state will then decay to the 0_1^+ ground state by an E0 transition. However upon closer look to the levelscheme of ^{202}Po , see figure 2.23, the 0_2^+ state lies at 1758 keV. Being able to populate a state this high in excitation energy seems unlikely. This reasoning is supported by the fact that no γ rays coming from other transitions, e.g. $4_1^+ \rightarrow 2_1^+$, are observed. This was the main reason for analyzing the ^{206}Po data, since the 0_2^+ state is not yet observed for this isotope and is expected to lie at very high excitation energy. Another possible cause of the large amount of X rays could be from other converted transitions but since no other γ de-excitation peaks were observed in any of the three experiments contributions associated with these de-excitations can be neglected. Thus the remaining amount of X rays should also be attributed to collisions. Table 3.9 shows then how the theoretical amount of X rays coming from collisions compares to the observed amount.

Target	Projectile	X_{coll}	Observed	Ratio
^{104}Pd	^{202}Po	90 (19)	511 (68)	5.7 (14)
^{94}Mo	^{202}Po	50 (21)	242 (60)	4.8 (24)
^{104}Pd	^{206}Po	82 (18)	166 (43)	2.0 (7)

Table 3.9 – Table showing the comparison between the theoretical amount of X rays due to collisions and the observed amount. The last column is the ratio between the two.

From table 3.9 some features emerge. The amount of expected X rays coming from collisions is comparable in the two experiments on the ^{104}Pd target implying that the total dose of incident polonium projectiles should be roughly the same. The predicted amount of X rays coming from K vacancy production in the ^{202}Po on ^{94}Mo experiment, is roughly half the value of the other two experiments thus the dose should in this case also be half the value of the other two experiments. The ratio in the last column of table 3.9 agrees, within error bars, for both the ^{202}Po experiments but is approximately a factor 2.5 higher than the ^{206}Po experiment. The cross sections for K-vacancy production in the polonium isotopes of interest have been calculated (σ_{theo}), these values have been corrected for the experimentally observed lower-lying values, the limited detection range of the DSSSD, the fluorescence and the relative branching for K_α and K_β emission. The results are summarized in table 3.10 together with the extracted incident dose.

Target	Projectile	Incident Dose [10^8]	σ_{theo} [barn]	σ_{exp} [barn]	Ratio
^{104}Pd	^{202}Po	7.9 (10)	0.0570 (99)	0.331 (68)	5.8 (16)
^{94}Mo	^{202}Po	4.8 (23)	0.0467 (82)	0.23 (13)	5.0 (28)
^{104}Pd	^{206}Po	7.1 (11)	0.058 (10)	0.120 (37)	2.1 (7)

Table 3.10 – Table showing the incident dose and the theoretically estimated cross sections for K vacancy production. The last two columns show the cross section extracted from experiments and the ratio between experiment and theory.

Table 3.10 proves the predictions that the dose for the two experiments on the palladium target is indeed nearly the same while the dose for the experiment on the molybdenum

target is approximately a factor of two lower. From the amount of X rays present in the data the experimental cross section for K-vacancy production can be calculated and this value can then be compared to the estimated one. Table 3.10 clearly shows that the experimental and theoretical cross section differ a factor of approximately 5 - 5.5 in the case of ^{202}Po and a factor of 2 in the case of ^{206}Po . It was already deduced that the excess X-ray counts did not originate from converted transitions since no other γ de-excitation peaks were observed but were attributed to K-vacancy production via collisions. As mentioned before, a large discrepancy between the estimated and experimental cross sections for K vacancy production was observed. However in the paper of N. Bree concerning the K-vacancy production in the mercury isotopes, this was not the case [Bre10]. In his paper the agreement between the expected amount of X rays and the observed amount of X rays for ^{188}Hg was considered satisfactory. For this isotope no E0 transition was expected. The excess X rays in the lighter isotopes could thus be attributed to the E0 $0_2^+ \rightarrow 0_1^+$ de-excitation [Bre10]. Since this is not the case in the $^{202,206}\text{Po}$ data, either something is wrong in the estimation of the cross section or an unknown nuclear or atomic process is at hand. Either way a more detailed look into this matter should be conducted to gain a more thorough understanding of the heavy-ion induced K-vacancy production and the origin of these X rays should be further investigated. A further improvement of the detection setup by addition of an electron detector could assist in the further exploration of this matter.

3.5 CLX analysis and Discussion

Now that the de-excitation yields are known, the relative cross section for Coulomb excitation and thus the $B(E2, 2^+ \rightarrow 0^+)$ value for ^{202}Po can be determined. The relative cross section is calculated using the computer code CLX. As described in section 1.3.6, CLX uses first-order perturbation theory to determine the excitation cross section. For the calculation a number of input parameters are necessary but does not include efficiency of the γ detection. The geometry of the detection setup is only partially included since the angular range of the DSSSD in the center-of-mass frame for the scattered particle is included. The states that are implemented in the CLX analysis are summarized in figure 3.22. When performing the CLX analysis formula 1.30 plays a crucial role. The matrix elements of the targets are known (thus the cross sections as well), the gamma yields have been previously extracted and the γ -detection efficiency is known as well, the only unknown is the relative cross section for Coulomb excitation for the projectile. By varying the transitional matrix element ($\langle 0_1^+ || E2 || 2_1^+ \rangle$) for projectile excitation in the CLX code, the relative cross section for populating the 2^+ state changes. This is done until equation 1.30 is satisfied. The result is shown in table 3.11.

The errors on the transitional matrix element, and $B(E2, 2^+ \rightarrow 0^+)$ value, are determined by extracting this matrix element for the upper and lower limit of the projectile de-excitation yield (1σ confidence level). An attempt was also made to determine the diagonal matrix element $\langle 2_1^+ || E2 || 2_1^+ \rangle$. As mentioned before the angular range of the DSSSD was divided into three center-of-mass ranges. Each of these center-of-mass ranges

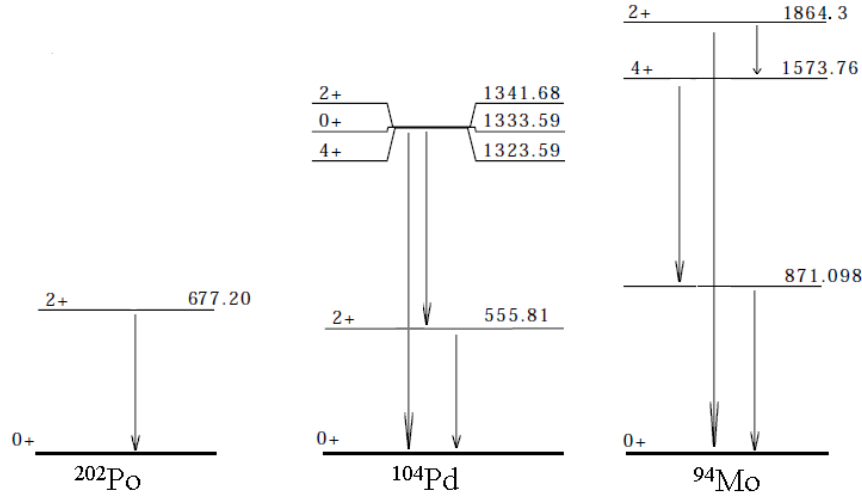


Figure 3.22 – The level scheme of the populated states as it is implemented in the CLX analysis. The matrix elements connecting these states added as well.

Target	Projectile	$\langle 0_1^+ E2 2_1^+ \rangle$ [eb]	B(E2) [W.u.]
^{104}Pd	^{202}Po	0.995 $\begin{pmatrix} 0.120 \\ 0.130 \end{pmatrix}$	28.1 $\begin{pmatrix} 72 \\ 69 \end{pmatrix}$
^{94}Mo	^{202}Po	0.990 $\begin{pmatrix} 0.180 \\ 0.205 \end{pmatrix}$	28 $\begin{pmatrix} 11 \\ 10 \end{pmatrix}$
Weighted average			28.0 $\begin{pmatrix} 60 \\ 57 \end{pmatrix}$

Table 3.11 – This table shows, for both ^{202}Po experiments, the extracted matrix element and corresponding $B(E2, 2^+ \rightarrow 0^+)$ value. The bottom row displays the weighted average. Please note that for this calculation, it was assumed that the quadrupole moment is equal to zero.

is then considered as a different experiment and for each of these experiments the transitional matrix element is determined in the same way as before (including the error bars). But now the diagonal matrix element is included and takes on different values. Since the transitional matrix element is a physical observable, the value that is extracted should be the same for the three experiments. Thus the value of the diagonal matrix element is the one for which the curve is the most constant. The result is shown in figure 3.23.

Figure 3.23 indicates that the diagonal matrix element should lie around 0 but to draw a more accurate conclusion the angular range of the DSSSD should be increased by including the 4 most inner strips of the DSSSD in the analysis. But due to the large error bars on the points either one of these curves could in fact be constant. Thus no definite conclusion about the diagonal matrix element could be drawn. This analysis was not performed for the ^{202}Po on ^{94}Mo experiment because of lack of statistics.

The $B(E2, 2^+ \rightarrow 0^+)$ value for ^{202}Po is 28.0 $\begin{pmatrix} 60 \\ 57 \end{pmatrix}$ W.u.. This corresponds to a transitional matrix element $\langle 0_1^+ || E2 || 2_1^+ \rangle = 0.993 \begin{pmatrix} 100 \\ 110 \end{pmatrix}$ eb and a lifetime of the 2_1^+ state of 2.91 $\begin{pmatrix} 62 \\ 59 \end{pmatrix}$ ps.

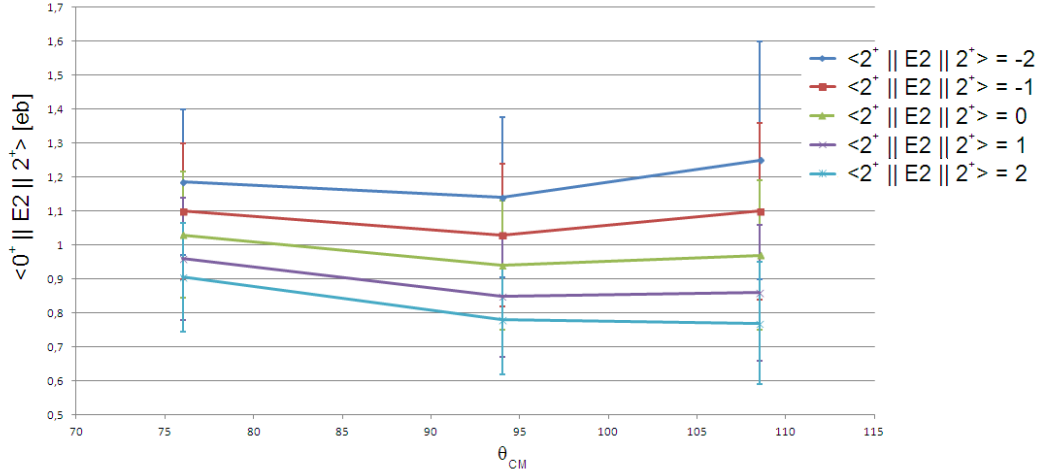


Figure 3.23 – This graph shows the transitional matrix element for the 3 different angular ranges plotted for different values of the diagonal matrix element for the ^{202}Po on ^{104}Pd experiment. Error bars are included and color indicated.

This lifetime confirms the previous assumption that the lifetime of the 2_1^+ state should be of the order of ps. Now the $B(E2, 2^+ \rightarrow 0^+)$ value can be compared to the previously known $B(E2, 2^+ \rightarrow 0^+)$ values of the polonium isotopes, see figure 3.24. The deduced value for ^{202}Po fits in the generalized seniority scheme and does not deviate much from its neighbor ^{200}Po . This was expected as both isotopes are very similar. This graph will in the future be completed by the addition of the $^{196,198,206}\text{Po}$ isotopes also measured during the Coulomb excitation campaign. This should allow a better understanding of the transition between the general seniority type behavior and the collective behavior.

To complete the analysis, a better understanding of the origin of the X rays is required. Once the origin is known a more complete population level scheme can be made (e.g. inclusion of the 0_2^+ state) and a more thorough analysis can be performed using the GOSIA programme for Coulomb excitation. Using GOSIA a value for the diagonal matrix element $\langle 2_1^+ || E2 || 2_1^+ \rangle$ might be extracted as well completing the analysis of ^{202}Po . Finally, a comparison with our result for ^{202}Po is made with recent beyond mean field calculations, see figure 3.25 [Yao13]. It is interesting to note that with respect to the $B(E2)$ values, good agreement between theory and experiment is observed, however for the excitation energies large discrepancies exist; e.g. the 2^+ excitation energy is predicted a factor of 2 to high.

The $B(E2, 2^+ \rightarrow 0^+)$ value extracted from the experiment agrees within error bars with the value calculated from beyond-mean-field calculations. From theory a prediction was made regarding the value of the diagonal matrix element, it is calculated to be $\langle 2_1^+ || E2 || 2_1^+ \rangle = 0.31$ eb corresponding to a vanishing quadrupole moment [Yao13]. Thus from theory spherical symmetry is expected for the ^{202}Po isotope which was also suggested from the review of Heyde and Wood [Hey11]. As mentioned before, no strong conclusion could be drawn for the diagonal matrix element from the experiment although a value around zero

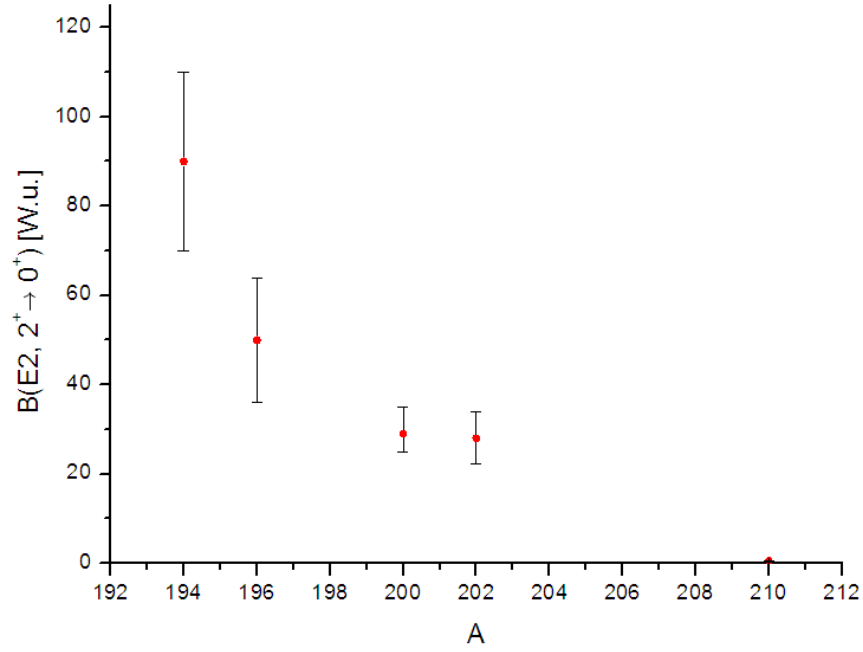


Figure 3.24 – Graph showing the known $B(E2, 2^+ \rightarrow 0^+)$ values of the polonium isotopes in Weisskopf units in function of the mass number A . The values for $^{194,196}\text{Po}$ are taken from [Gra09], the value for ^{200}Po is taken from [Kes10] and the value for ^{210}Po from [Ell73].

was compatible.

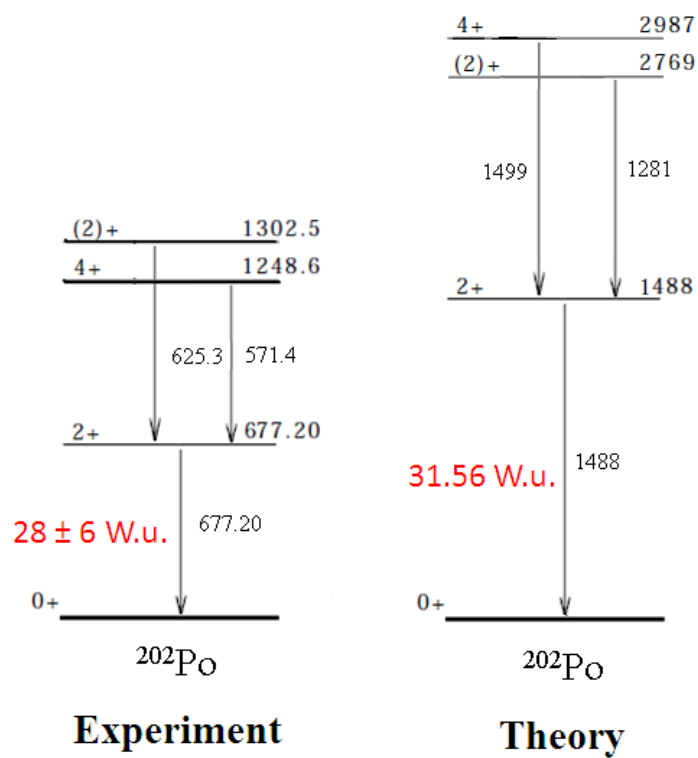


Figure 3.25 – Figure comparing the theoretical level scheme with the experimentally observed level scheme. In red is the $B(E2, 2^+ \rightarrow 0^+)$ value calculated from theory and experiment [Yao13].

Conclusion

The polonium isotopes with two protons outside the $Z = 82$ shell represent an interesting region of the nuclear chart. In the lightest polonium isotopes the interplay of the spherical and deformed structures is responsible for the perturbation of the energy systematics, resulting in shape coexistence. When neutrons are added the transition from a collective behavior to a "regular seniority-type regime" is observed. Questions remain however concerning the transition between these two modes and the degree of mixing between different configurations. In a recent experiment the $^{196,198,200,202}\text{Po}$ isotopes were investigated using Coulomb excitation. In this thesis work the results from ^{202}Po and ^{206}Po are presented and discussed.

In a Coulomb excitation experiment, a high-energy projectile is inelastically scattered off a stationary target. Through the exchange of virtual photons due to the electromagnetic interaction, low-lying excited states in the projectile or target can be populated. The cross section for Coulomb excitation depends in first order on the $B(E2, 2^+ \rightarrow 0^+)$ value and in second order on the diagonal matrix element of the populated states. From this experiment the $B(E2, 2^+ \rightarrow 0^+)$ value could be extracted and renders a direct measure of the collectivity of the nucleus. The focus of this work was also on the X-ray production and two possible origins were discussed: X rays originating from collisions and X rays originating from conversion electrons. In the context of the latter study, the ^{206}Po on ^{104}Pd experiment was analyzed as well.

At REX-ISOLDE (CERN) a 2.85 MeV/u beam of $^{202,206}\text{Po}$ beam was created. The beam was then guided towards the target chamber where it impinged on the target (either ^{104}Pd or ^{94}Mo). The Coulomb excitation events were detected using the Miniball detection setup consisting of a double-sided silicon-strip detector for detecting the scattered nuclei and the Miniball γ spectrometer for detecting the emitted γ rays. The calibration of both detectors was explained and an absolute efficiency curve, using ^{133}Ba and ^{152}Eu , data was extracted.

A Coulomb-excitation event consists of the detection of two coincident particles, scattered back-to-back in the center-of-mass frame, and the detection of a γ ray coincident with these particles. First the Coulomb-excitation events were selected using information from the timing spectrum and kinematics spectrum. A problem concerning the downscal-

ing made it impossible to restrict the statistics in the analysis of the 2-particle events and the one-particle events were selected as well. The resulting γ spectrum showed Doppler broadening of the de-excitation peaks due to the γ rays being emitted in flight. Therefore a Doppler correction was performed on this gamma γ spectrum. The number of counts in the de-excitation peaks of target and projectile were then determined.

Apart from the de-excitation peaks, a large number of X rays were visible in the γ spectrum. The origin of these X rays was further investigated. Part of the X rays were attributed to conversion electrons originating from $2_1^+ \rightarrow 0_1^+$ de-excitation. From phenomenological theory and previous work, the amount of X rays coming from heavy-ion induced K-vacancy creation can be estimated. Comparison was then made between the amount of observed X rays and the amount predicted by theory. A large number of X-ray counts were unaccounted for in the ^{202}Po experiments. Since no other projectile de-excitation peak was observed, the possibility was explored that these counts originated from the E0 transition of the 0_2^+ state to the ground state. This transition was already observed in the EC/ β -decay study by Bijmens et al. [Bij98]. Therefore the ^{206}Po data was analyzed as well since no low-lying 0_2^+ state is expected in this nucleus. A large amount of X rays remained unexplained as well in this experiment implying that the large amount of X rays did not originate from the E0 transition. Experimental and estimated cross sections were calculated and compared and it was observed that the experimental cross sections deviated significantly from the estimated value. To complete the analysis comparison was also made with a previous experiment concerning the mercury isotopes of Bree et al. [Bre10]. It was then concluded that a more detailed look should be conducted on this matter in order to understand the origin of these X rays and the addition of an electron detector to the detection setup was suggested.

Using the CLX analysis code the value for the transitional matrix element $\langle 0_1^+ || E2 || 2_1^+ \rangle = 0.993 \left(\frac{100}{110} \right)$ eb was extracted corresponding to a $B(E2, 2^+ \rightarrow 0^+)$ value of 28.0 $\left(\frac{60}{57} \right)$ W.u.. The lifetime of the 2_1^+ state was calculated to be 2.91 $\left(\frac{62}{59} \right)$ ps. The extracted $B(E2, 2^+ \rightarrow 0^+)$ value was then compared to the previously known $B(E2, 2^+ \rightarrow 0^+)$ values of other investigated polonium isotopes. It was concluded that the $B(E2, 2^+ \rightarrow 0^+)$ value for ^{202}Po fits in the generalized seniority scheme. A further comparison revealed that this $B(E2, 2^+ \rightarrow 0^+)$ is in good agreement with the value expected from beyond mean field calculations however for the excitation energies large discrepancies exist between experiment and theory. This data will be further completed with the addition of the $^{196,198,206}\text{Po}$ $B(E2, 2^+ \rightarrow 0^+)$ values, also part of the same experimental campaign. The basics for the analysis strategy of these isotopes has been set with the completion of this work. No conclusion could be drawn about the diagonal matrix element $\langle 2_1^+ || E2 || 2_1^+ \rangle$ due to low statistics. It was then suggested to gain a more deeper understanding of the origin of the X rays so that a more complete analysis can be performed using the GOSIA programme.

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