

Study of the $^{66}\text{Ni}(t,d)^{67}\text{Ni}$ Transfer Reaction in Inverse Kinematics

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Nederlandstalige samenvatting

De nikkel isotopen met 28 protonen zijn een interessante reeks in de studie naar de interne structuur van atoomkernen. De uiterst exotische isotopen van nikkel zijn de proton rijke kern ^{48}Ni met 20 neutronen en de neutron rijke kern ^{78}Ni met 50 neutronen. Die laatste kern wordt beschouwd als een belangrijke kern in de nucleosynthese. Bij extreem hoge neutronenfluxen, zoals in supernovae, gaan kernen zeer snel neutronen absorberen, dit proces wordt het r -proces genoemd. ^{78}Ni wordt beschouwd als een wachtpunt in het r -proces, het proces houdt halt en wacht op het verval van deze kern [Hea05].

Al tientallen jaren wordt uitvoerig onderzoek gedaan naar hoe de structuur van de nikkel isotopen verandert naarmate neutronen toegevoegd worden. Een opmerkelijke observatie werd gedaan bij ^{68}Ni . Deze kern met 40 neutronen vertoont karakteristieke eigenschappen van dubbel magische kernen. Met name de energie van de eerste 2^+ toestand is beduidend hoger dan in de naburige nikkel isotopen met een even aantal nucleonen. Bovendien is ook de overgangswaarschijnlijkheid $B(E2 : 0_1^+ \rightarrow 2_1^+)$ kleiner dan in de naburige isotopen met een even aantal nucleonen. Deze bevindingen kunnen wijzen op een groot energieverschil tussen het $2p_{1/2}$ schillen model orbitaal en het $1g_{9/2}$ orbitaal. Om deze hypothese te testen werd de massa en de bindingsenergie van de neutronen van ^{68}Ni gemeten. Deze metingen tonen aan dat $N = 40$ geen magisch karakter heeft. Ook uitgebreide theoretische berekeningen in het kader van het schillen model tonen aan dat $N = 40$ geen uitgesproken magisch karakter heeft.

Om meer duidelijkheid te scheppen over de structuur van ^{68}Ni werd in 2011 in de ISOLDE faciliteit in CERN een transfer reactie uitgevoerd. In deze transfer reactie werden ^3H kernen beschoten met een radioactieve ^{66}Ni bundel. De gewenste reactiekanalen zijn $^{67}\text{Ni} + ^2\text{H}$ ($Q = -0.45$ MeV) en $^{68}\text{Ni} + ^1\text{H}$ ($Q = 5.12$ MeV). Die laatste biedt de mogelijkheid om op een directe manier geëxciteerde toestanden van ^{68}Ni te bevolken. Naast de energie van de toestanden kan uit de angulaire distributie van de protonen ook hun spin en pariteit bepaald worden. De angulaire distributie van de reactieproducten heeft namelijk een specifieke hoekafhankelijkheid die gerelateerd is aan het getransferreerde impulsmoment. In deze thesis werd het $^{67}\text{Ni} + ^2\text{H}$ reactiekanaal geanalyseerd. Deze reactie biedt inzicht in de laag-energetische structuur van ^{67}Ni , daarnaast biedt dit reactiekanaal ook de mogelijkheid om de structuur van ^{68}Ni te bestuderen. Transfer reacties zijn een vaak gebruikte techniek om het één-deeltje karakter van de bevolkte toestanden te bepalen. De experimentele werkzame doorsnede is hier van centraal belang. Deze kan getoetst worden met theoretische waarden berekend met de DWBA (Distorted-Wave Born Approximation) theorie. Deze succesvolle theorie wordt beschouwd als een betrouwbaar theoretisch kader voor de beschrijving van transfer reacties, zelfs in het geval van exotische kernen zoals ^{67}Ni . De spectroscopische factoren die hieruit afgeleid kunnen worden geven weer hoe sterk de bevolkte toestand overeenkomt met een pure één-deeltjes toestand in het schillen model. Kernen die slechts met één nucleon afwijken van een dubbel magische structuur zijn in het algemeen zeer goed te beschrijven in het één-deeltje model. Op die manier is het één-deeltje karakter van ^{67}Ni een indirecte probe voor de magiciteit van ^{68}Ni .

Het experiment werd uitgevoerd in ISOLDE, dit is een afdeling in CERN waar een breed scala van exotische radioactieve elementen geproduceerd kan worden. In de REX-ISOLDE bundellijn werd een radioactieve bundel van ^{66}Ni gepulst en versneld tot 171.6 MeV. Deze

energie is nodig opdat transfer reacties zouden kunnen plaatsvinden. De kinetische energie van kernen moet hoog genoeg zijn om de Coulomb barrière te doordringen en via de sterke kernkracht te interageren.

Het detectiesysteem bestaat uit de Miniball + T-REX opstelling. T-REX is een rooster van silicium strip detectoren om geladen deeltjes te detecteren. Deze detectoren worden binnenin de vacuumkamer geplaatst, zowel in voorwaartse als achterwaartse richting en omvatten 66% van de totale ruimtehoek. De Si detectoren zijn gesegmenteerd zodat de angulaire distributie bepaald kan worden. De detectoren hebben ook een telescoop configuratie die toelaat protonen, deuterium, tritium en andere geladen deeltjes met lage massa te identificeren. Deze identificatie gebeurt op basis van de positie in ΔE - E grafieken. Zo is het mogelijk de verschillende reactiekanalen individueel te analyseren. Naast T-REX is er Miniball, dit is een opstelling van germanium detectoren om γ stralen te detecteren. De detectoren worden buiten de vacuumkamer geplaatst en omringen zo de trefschijf die ^3H bevat, de gemiddelde detectie efficiëntie bedraagt ongeveer 6% voor een 1 MeV γ straal. De Ge detectoren hebben als doel de γ stralen van het verval van ^{67}Ni of ^{68}Ni te meten. Deze kernen bewegen echter met hoge snelheid door de setup, daarom werd een Doppler correctie toegepast om de resolutie te verhogen.

In de data analyse werd de $^2\text{H} + ^{67}\text{Ni}$ partitie geselecteerd. Door middel van d - γ en d - γ - γ coincidenties werd de structuur van ^{67}Ni bestudeerd. De energie en intensiteit van de γ stralen werd gemeten, dit geeft ons heel wat informatie over de laag energetische structuur van ^{67}Ni . Uit de energie van de uitgezonden deuterium kernen werd afgeleid dat geëxciteerde toestanden tot 3.6 MeV bevolkt worden. De geobserveerde toestanden komen overeen met de literatuur [Jea05] en de voorgestelde interne structuur van ^{67}Ni in [Dir13]. De angulaire distributie van de grondtoestand en drie geëxciteerde toestanden werd geconstrueerd. Uit de elastische verstrooiing van tritium werd de normalisatiefactor en gemiddelde bundelintensiteit bepaald, i.e. $2.5(3) \cdot 10^6$ pps. De experimentele angulaire distributie werd vergeleken met DWBA berekeningen. Omdat deuterium echter enkel in hoge CM hoeken gedetecteerd kon worden, is het niet mogelijk duidelijk onderscheid te maken tussen de verschillende ℓ -transfer reacties. Bijgevolg kon de spin en pariteit niet bepaald worden.

Deze thesis is onderverdeeld in vijf hoofdstukken. In het eerste hoofdstuk wordt het belang van dit experiment gemotiveerd. Het tweede hoofdstuk beschrijft de experimentele opstelling, meer bepaald de ISOLDE faciliteit waar de radioactieve bundel geproduceerd wordt en de detectoren om de reactie te bestuderen. Het derde hoofdstuk handelt over het theoretisch kader om kernreacties te beschrijven, de nadruk ligt hier vooral op transfer reacties. Het vierde hoofdstuk beschrijft hoe de data geanalyseerd werden en bevat ook de bekomen resultaten. In het laatste hoofdstuk wordt een conclusie gemaakt van het experiment.

Summary

The nickel isotopes with 28 protons are an interesting series in the study of nuclear structure. In the framework of the shell model nickel has a closed proton shell and the number of neutrons ranges from the magic numbers 20 to 50. The neutron-rich isotope ^{78}Ni , is a waiting point in the nucleosynthesis r -process. In this process an intense neutron flux such as in supernovae results in the rapid capture of neutrons. The reaction sequence halts at ^{78}Ni and waits for this nucleus to decay [Hea05].

For several decades the nickel isotopes have been studied extensively, particularly how the nuclear structure evolves when moving to the exotic boundaries of the nuclear chart. A remarkable feature was observed in ^{68}Ni . This nucleus with 40 neutrons exhibits properties that are characteristic for doubly magic nuclei. Such as the energy of the first 2^+ state lies significantly higher than in neighbouring even- A isotopes, and is also higher than the energy of the second 0^+ state. Moreover also the $B(E2 : 0_1^+ \rightarrow 2_1^+)$ transition probability is lower than in neighbouring isotopes. These observations may indicate that the energy gap between the $2p_{1/2}$ and $1g_{9/2}$ shell model orbitals on both sides of the $N = 40$ gap is large and ^{68}Ni could be called a semi-magic nucleus. To test this hypothesis mass measurements of the nickel isotopes have been performed. From these measurements however ^{68}Ni does not behave as would be expected for a magic nucleus. Besides these mass measurements, also large scale shell model calculations point out ^{68}Ni is no magic nucleus. Due to the parity change in the pf and dg orbitals, ^{68}Ni mimics typical features of doubly-magic nuclei.

To gain more insight in the nature of the internal states of ^{68}Ni a transfer reaction experiment was performed at the REX-ISOLDE facility in CERN. A radioactive beam of ^{66}Ni produced at the ISOLDE facility impinges on a target containing ^3H . The reaction channels of interest are $^{67}\text{Ni} + ^2\text{H}$ ($Q = -0.45$ MeV) and $^{68}\text{Ni} + ^1\text{H}$ ($Q = 5.12$ MeV). The latter offers a means to directly populate excited states of ^{68}Ni . This way the energy of the nuclear states can be determined. Moreover from conservation of spin and parity in the reaction the possible spin and parity configurations of the energy levels can be deduced from the angular distribution of the emitted protons. The angular distribution is intimately related to the transferred angular momentum. In this thesis the $^{67}\text{Ni} + ^2\text{H}$ partition has been analysed. This reaction provides insight in the low energy structure of ^{67}Ni . In addition, the structure of this nucleus offers a means to study the magic character of ^{68}Ni . One nucleon transfer reactions are excellent probes for the single-particle character of nuclei. In these studies the differential cross section as function of the angle is of ample importance. The experimental differential cross section can be compared to theoretical DWBA calculations from which spectroscopic factors can be deduced. The spectroscopic factor represents how well the populated state in ^{67}Ni correspond to ^{66}Ni plus a neutron in a particular shell model orbital. Nuclei which differ from doubly-magic nuclei are very well described by the independent single-particle model. In this perspective the single-particle character of ^{67}Ni is an indirect probe of the magicity of ^{68}Ni .

The experiment has been performed at the ISOLDE facility at CERN, this facility is dedicated to the study of exotic nuclei. A large variety of exotic radioactive beams can be produced. At the REX-ISOLDE beamline a beam of ^{66}Ni is shaped, pulsed and post-accelerated to 2.6 MeV/A. This energy is needed to penetrate through the Coulomb

barrier and induce transfer reactions through the strong, short-ranged nuclear force.

The detection system is equipped with the T-REX and Miniball setup. T-REX is an array of silicon strip detectors to detect charged particles. The detectors are placed inside the target chamber both in forward and backward direction from the target and cover about 66% of the total solid angle. This wide detection range is necessary in transfer experiments in inverse kinematics. The silicon detectors are segmented such that the angular distribution can be reconstructed. Furthermore the detectors have a telescope configuration which allows to identify protons, deuterons, tritons and other light charged particles. The identification is based on the position in ΔE - E plots. This way one can discriminate different reaction channels in the experiment. Besides the T-REX array there is the Miniball setup, Miniball is an array of eight clusters of three six-fold segmented HPGe detectors. The germanium detectors are placed outside the target chamber and surround the target, the total detection efficiency of a 1 MeV γ ray is about 6%. The detectors are used to detect γ rays from the decay of ^{67}Ni and ^{68}Ni . These nuclei move through the target chamber with high velocities of about $0.07c$. Consequently it is necessary to Doppler correct the γ spectrum to increase the energy resolution.

The data analysis in this thesis focuses on the $^{67}\text{Ni} + ^2\text{H}$ partition. By means of d - γ and d - γ - γ coincidence gates the decay of ^{67}Ni is investigated. Low energy states of ^{67}Ni could be identified. From the energy of the deuterons it can be seen that excited states up to 3.6 MeV are populated. The observations are in agreement with the literature [Jea05] and the proposed level scheme based on the $^{66}\text{Ni}(d, p)^{67}\text{Ni}$ reaction [Dir13]. The angular distribution of the ground state and three low excited states has been reconstructed. From the elastic channel $^{66}\text{Ni}(t, t)^{66}\text{Ni}$ the normalization factor and average beam intensity has been calculated, i.e. $2.5(3) \cdot 10^6$ pps. The differential cross section has been compared to DWBA calculations performed with Fresco [Tho88]. The experimental data on the (t, d) reaction is limited to high CM angles. At these angles, far from the position of the first maximum, it is impossible to determine the transferred angular momentum. Consequently no spin and parity assignments are done and no spectroscopic factors could be deduced.

This thesis consists of five chapters. In the first chapter the motivation for this experiment is described. In the second chapter the experimental setup at ISOLDE and the detection setup are presented. The third chapter gives an introduction to scattering theory and reaction theory with a focus on transfer reactions. In the fourth chapter the data analysis is described and the obtained results are presented. In the last chapter the conclusions of this experiment are given.

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Chapter 1

Motivation and Physics Case

1.1 Nuclear Physics

Nuclear physicists study the inner core of atoms, called *nuclei*. Nuclei are composed of nucleons, of which two types can be discriminated, namely *protons* and *neutrons*. Protons are positively charged particles and neutrons have no charge. The number of protons in a nucleus (Z), together with the electron cloud determines the chemical properties of the atom. The number of neutrons (N) can vary, nuclei with the same Z but different N are called *isotopes*. The chemical properties of isotopes are the same but the nuclear properties can be very different. Nuclei are commonly represented in the following way A_ZX , where $A = N + Z$ is the total number of nucleons in a nucleus.

Even though positively charged protons repel each other due to the *electromagnetic force*, it is found that they are closely packed in nuclei. This is possible since on the femtometer scale (10^{-15} m) there is a strong attractive force between nucleons that can overrule the electromagnetic force. This force is called the *strong force*. However nuclei with only protons do not exist (except for ${}^1_1\text{H}$), neutrons are necessary to make the nucleons stick together.

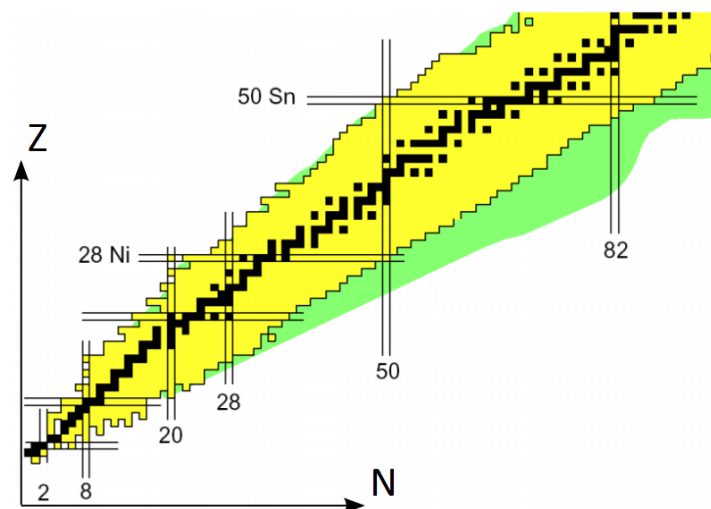


Figure 1.1: Table of isotopes.

In figure 1.1 a part of the nuclear chart is shown, the nuclear chart contains all the bound systems of protons and neutrons, each box represents an isotope. On the horizontal axis the number of neutrons N is shown, on the vertical axis the number of protons Z . The black boxes represent stable nuclei, along the chart they form the *valley of stability*. The yellow squares represent unstable radioactive nuclei of which the mass has been measured, the green area corresponds to nuclei that have been observed but of which the mass has not been measured. The unstable nuclei decay¹ step by step by emitting radiation until they reach the valley of stability. One type of decay, namely β -decay, is governed by the *weak force*. This is a third important force in nuclear systems. Nuclei that lie far from the valley of stability are called *exotic nuclei*. In general, nuclei that lie far from the valley of stability decay faster. The goal of nuclear physicists is to gain more insight in the interplay of the electromagnetic force, strong force and the weak force in nuclei². In other words to understand how nucleons interact with each other and form nuclei.

1.2 The Nuclear Shell Model

The nuclear shell model is one of the most successful models to describe the properties of nuclei. The model considers the nucleus as a collection of nucleons that move in quantized orbits. The idea originates from atomic physics where electrons are considered to move in atomic orbitals. For many nuclei, close to the valley of stability (actually near major closed shell configurations) the shell model proved to be very suited.

A lot of properties of nuclei can be described, moreover it allows to intuitively look at how nuclei are built up. The first indications of a shell structure in nuclei arose from the observed variation in neutron and proton binding energies. The neutron and proton separation energy decreases gradually with increasing N or Z respectively, except for a few sharp peaks at the protons or neutrons numbers:

$$2, 8, 20, 28, 50, 82 \text{ and } 126.$$

These so-called *magic numbers* are believed to correspond to the occupation numbers of filled major shells [Kra88]. In the following a brief description of the nuclear shell model will be given.

1.2.1 The Mean Field Approximation

The nucleus is a system of A interacting particles, thus in principle it is possible to determine the properties of nuclei by taking into account all the interactions between all the protons and neutrons. One can calculate the energy eigenvalues E and eigenstates or wave functions Ψ from the Schrödinger equation $H\Psi = E\Psi$ when the Hamiltonian H of the A -nucleon system, which contains the sum of the kinetic and potential energy of the particles, is known. The non-relativistic³ Hamiltonian of a nuclear system of A nucleons

¹Examples of decay mechanisms are β decay, α decay, electron capture, nucleon emission and fission[Kra88].

²A fourth elementary force in the Standard Model is the gravitational force. This force however is 10^{38} times smaller than the strong force and has no significant influence on the properties of nuclei.

³For low excitation energies (< 8 MeV), significantly smaller than the rest mass of protons (938.272 MeV/ c^2) and neutrons (939.565 MeV/ c^2), the non-relativistic Hamiltonian is a good approximation.

can be written as

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

where T_i is the kinetic energy of nucleon i and $V_{i,j}$ is the two-body interaction between nucleons i and j . This two-body interaction depends on the relative position of the nucleons. Unfortunately, a complete theoretical description of the strong interaction between nucleons is not known to date. It is therefore not possible to calculate the energy eigenvalues and wave functions in this way. The approach that is often taken is to make use of *mean field approximations*. In these approximations it is assumed that all protons or neutrons move independently in a mean field potential induced by all other nucleons. The model Hamiltonian for the A nucleons as independent particles can be written as

$$H_0 = \sum_{i=1}^A (T_i + U(\mathbf{r}_i))$$

where $U(\mathbf{r}_i)$ is mean field potential at the position of nucleon i . The great advantage of this approach is that the Schrödinger equation can be solved for one particle, since the Hamiltonian does not depend on the relative interaction between two nucleons. The non-relativistic A -body Hamiltonian from equation (1.1) can now be written as

$$\begin{aligned} H &= \sum_{i=1}^A [T_i + U(\mathbf{r}_i)] + \left(\frac{1}{2} \sum_{i,j=1}^A V_{i,j} - \sum_{i=1}^A U(\mathbf{r}_i) \right) \\ &= H_0 + H_{res}, \end{aligned} \quad (1.2)$$

where H_0 describes the motion of A nucleons in the same average field $U(\mathbf{r})$. In practice the Schrödinger equation is solved for H_0 and H_{res} is treated as a perturbation [Hey90]. The mean field approximation is a good approximation if the effect of H_{res} resembling the *residual interactions* is small. Many different models of the potential $U(\mathbf{r})$ in H_0 have been developed to describe the structure of nuclei, one of the most successful models is the *nuclear shell model* developed by several physicists, most notably Eugene Paul Wigner, Maria Goeppert-Mayer [May49], O. Haxel and J.H.D. Jensen [HJS49].

1.2.2 The Shell Model and Residual Interactions

The main ingredients of this nuclear shell model potential $U(\mathbf{r})$ are a *harmonic oscillator potential*, *pairing interactions* and *spin-orbit interactions*. The first versions of the nuclear shell model were based on a harmonic oscillator potential or a square well potential and a centrifugal term ($\sim l^2$), where l is the orbital angular momentum quantum number. With this model the lowest magic numbers were reproduced, namely 2, 8 and 20. For higher A , the predicted number of nucleons at which large shell gaps appear, i.e. 40, 70, ... did not match the experimentally observed numbers 28, 50, 82, 126, In further developments, a spin-orbit term, coupling the intrinsic spin $\mathbf{s}$ of a nucleon to the orbital angular momentum $\mathbf{l}$, was introduced. Such a spin-orbit interaction is well known in atomic physics⁴. In nuclei

⁴In atomic physics the spin-orbit interaction causes the fine-structure of the electronic levels of the atomic electrons.

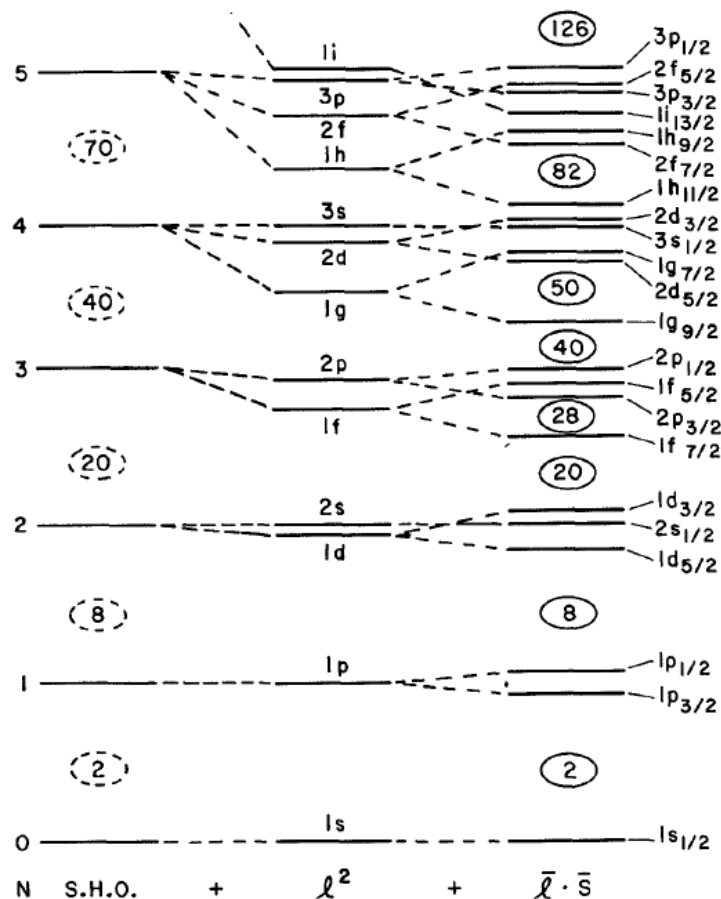


Figure 1.2: On the left, quantized energy levels resulting from a simple harmonic oscillator (S.H.O.) potential. In the middle, a simple harmonic oscillator potential with l^2 term. On the right, addition of the spin-orbit term, $V_{so}(r) \mathbf{l} \cdot \mathbf{s}$ [Cas00].

this force is of great importance, with this interaction taken into account the observed magic numbers can be reproduced. In figure 1.2 the effect of the different interaction terms on the energy levels is shown.

The spin-orbit interaction, $V_{so}(r) \mathbf{l} \cdot \mathbf{s}$, where $V_{so}(r)$ is the amplitude of the interaction⁵, causes a splitting and reordering of the levels, giving the proper separation of the energy levels or *orbitals*. Energy levels with $l > 0$ are split in two levels corresponding to $l \pm \frac{1}{2}$. It is appropriate to label the energy levels by Nl_j , where j is the total angular momentum quantum number $\mathbf{j} = \mathbf{l} + \mathbf{s}$, l corresponds to the orbital angular momentum (s for $l = 0$, p for $l = 1$, d for $l = 2$, etc.). N denotes the order of the state with a certain l . For instance the $2p_{1/2}$ orbital is the second p orbital with angular momentum $j = 1/2$. In this picture nuclei are thus described by a collection of nucleons moving in orbitals with a specific energy and wave function. From the *Pauli exclusion principle*⁶ it follows that the maximum occupation number of an orbital with quantum number j is $2j + 1$. At the occupations numbers 2, 8, 20, 28, 50, 82 and 126 gaps appear between the energy levels,

⁵The amplitude of spin-orbit interaction $V_{so}(r)$ is often taken as the derivative of the mean field potential, e.g. the derivative of a Woods-Saxon potential, which is maximal at the surface [Cas00]. The spin-orbit interaction is therefore called a surface interaction.

⁶The Pauli principle states that two fermions may not occupy the same quantum state simultaneously.

corresponding to major shell closures.

The description of independent nucleons moving in discrete orbitals in a mean field potential is an excellent approximation when there are no nucleons outside closed shells. When dealing with nuclei with valence nucleons⁷ *residual interactions*, not encompassed in the potential $U(\mathbf{r})$, have to be considered. In the case there is only one valence nucleon, we often use the *extreme independent particle model* to describe the nuclear structure. The total angular momentum J of the nucleus⁸ is determined by the motion of the single unpaired nucleon in orbital j since a closed major shell configuration is spherically symmetric and has $\mathbf{J}_{\text{full shell}} = 0$. The same is true for a configuration where one nucleon is missing to fill a shell, again the nuclear spin J depends only on the nucleon spin since $\mathbf{J}_{\text{full shell}} - \mathbf{j} = 0$, this configuration is called a *hole state*. The total angular momentum J of the ground state and excited states of a nucleus are thus given by the j value of the orbits in which the last odd nucleon can be placed [Cas00]. This model is only a first approximation, in general more effects play a role for instance when a pair of nucleons breaks and their spin couples to e.g spin 2 etc.

To describe nuclei with more than one valence nucleon different approaches are used depending on how far N and Z lie from magic numbers. For instance the structure of $^{169}_{70}\text{Yb}_{99}$, which is non-spherical and strongly deformed, can be explained in the framework of the *Nilsson model*. Far from closed shells *collective models* starting from a more macroscopic point of view are successful in describing the nuclear structure by means of rotational and vibrational states.

Nuclei with N and Z close to magic numbers but with a few valence nucleons, for instance $^{43}_{20}\text{Ca}_{23}$, are best described in the nuclear shell model taking into account *residual interactions* between valence nucleons. This model will also be used to describe the properties of the $_{28}\text{Ni}$ isotopes, in particular ^{67}Ni and ^{68}Ni . The term H_{res} in equation 1.2 represents the residual interactions between the valence nucleons. This nucleon-nucleon interaction shifts the energy of the excited states and ground state, altering the configuration of the energy levels. One way to approximate this interaction is by the short-ranged δ -interaction, the residual interaction potential V_{res} is then proportional to $\delta(\mathbf{r}_1 - \mathbf{r}_2)$. Many aspects of the residual interaction between valence nucleons can be reproduced with a δ function, such as the ordering of the excited states in many even- A nuclei. In the presence of this attractive residual interaction the energy of a state J formed by the coupling of a nucleon in orbital j_1 and a nucleon in orbital j_2 in even- A nuclei shifts,

$$\Delta E(j_1 j_2 J) = \frac{1}{\sqrt{2J+1}} \langle j_1 j_2 J | V_{\text{res}} | j_1 j_2 J \rangle. \quad (1.3)$$

In the absence of residual interactions states with the same spin J would be degenerate. Another more general approach to describe the residual interaction potential is to consider a multipole decomposition of a potential that depends on the separation of two particles,

$$V_{\text{res}}(|\mathbf{r}_1 - \mathbf{r}_2|) = \sum_k^{\infty} \nu_k(r_1 r_2) P_k(\cos\theta), \quad (1.4)$$

⁷Valence nucleons are nucleons moving in orbitals outside major closed shells.

⁸The model is successful in accounting for the spins and parities of odd- A nuclei, to a lesser extent in accounting for the magnetic dipole and electric quadrupole moments [Kra88].

where $P_k(\cos \theta)$ are the Legendre polynomials, θ is the angle between the angular momentum vectors $\mathbf{j}$ of particles 1 and 2. In this description the monopole term ($k = 0$) affects all states equally and simply gives an overall shift to all states. This term is directly related to the mass dependence of the separation energy. Higher order terms cause energy shifts between the levels, for instance the quadrupole term ($k = 2$) lowers the energy of the lowest and highest spin states J when $j_1 + j_2 + J$ is even. This description is very successful in predicting the structure of nuclei near magic numbers.

When moving further away from the valley the ratio N/Z changes⁹, consequently the energy levels will shift [Dea94] since the nuclear potential and residual interactions are closely connected to this ratio. It is expected that the influence of the spin-orbit term will decrease as nuclei become more neutron-rich [Oea01]. The orbital ordering tends to lose its grouped structure which gave rise to the magic numbers (8, 20, 28,...). The levels now shift towards an equidistant level structure. In this evolution, new shell gaps appear and other magic numbers arise, while magic numbers that are valid near the valley of stability disappear. To study this evolution of the energy levels, experimental parameters that are closely connected to the magicity of nuclei are observed. These experimental observables will be discussed in the following.

1.2.3 Experimental Observables

Mass, Binding Energy and Separation Energy

A first experimental parameter related to nuclear structure is the nuclear mass. The mass of a nucleus is less than the sum of the masses of its constituents. This mass difference is related to the binding energy (BE) of a nucleus via $\Delta E = \Delta mc^2$. The binding energy is related to the fact that the nuclear force is predominantly attractive, energy minimization requires nucleons to be bound at short distances instead of unbound [Kra88]. The binding energy per nucleon is shown in figure 1.3.

One of the first nuclear models, the *liquid drop model*, successfully described this observation by means of a semi-empirical mass formula:

$$BE = a_v A - a_s A^{2/3} - a_C Z(Z-1)A^{-1/3} - a_a \frac{(N-Z)^2}{A} + (\delta, 0, \text{or } -\delta)$$

where a_v , a_s , a_C , a_a and δ are the coefficients of the volume, surface, Coulomb, asymmetry and pairing terms. The pairing term is 0 for odd- A nuclei, $+\delta$ for even-even nuclei, and $-\delta$ for odd-odd nuclei, such that even-even configurations are favored [Kra88]. The fit parameters are obtained by fitting this function to the experimentally determined binding energy from mass measurements of nuclei. Related to the nuclear binding energy, is the the proton and neutron separation energy, $S_p = [m({}_Z^A X_N) - m({}_Z^{A-1} Y_N) - m(p)] c^2$ and $S_n = [m({}_Z^A X_N) - m({}_Z^{A-1} Y_{N-1}) - m(n)] c^2$, respectively. The separation energy is measure of how strong a nucleon is bound in the nucleus. It is large in doubly magic nuclei and low for nuclei with valence nucleons outside closed shells. From the liquid drop model this can not be explained but from the shell model it can. Usually to study the magic character of nuclei, the two-proton (S_{2p}) or two-neutron (S_{2n}) separation energy is measured since it excludes the pairing interaction effect. S_{2p} and S_{2n} are considered to be the most direct probes to study the magic properties of nuclei.

⁹With respect to the value of N/Z of stable nuclei.

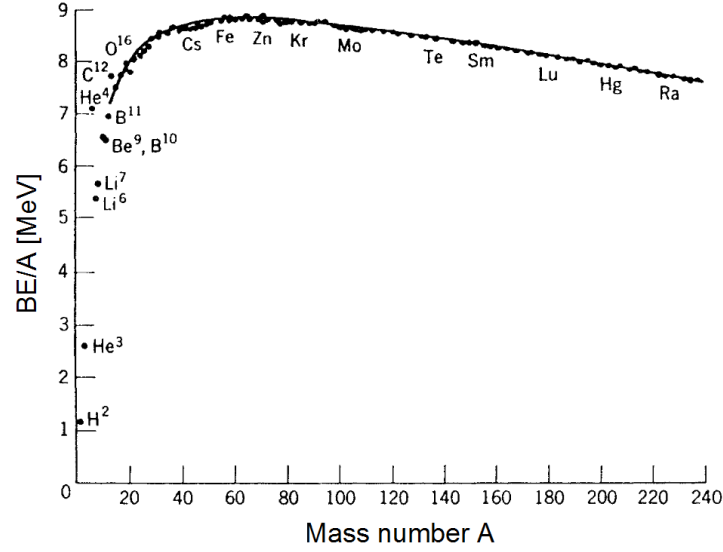


Figure 1.3: Binding energy per nucleon versus nucleon number from [ER74].

Energy of the First Excited State

The ground state spin and parity J^π of even-even nuclei is always 0^+ and the first excited state is nearly always a 2^+ state [Cas00]. The energy of this 2^+ state, denoted as E_{2^+} , is significantly higher for doubly magic nuclei than in neighbouring even-even nuclei. To excite a nucleus to the first state a nucleon from the closed shell has to be excited to a more energetic orbital. For magic nuclei the first orbital to which the nucleon can be excited to, lies higher than for non-magic nuclei. Consequently the energy of the first excited state (most often a 2^+ state) is a measure of the energy gap between orbitals.

B(E2) Transition Strength

Nuclear excited states can decay via the emission of a photon. The photon (or electromagnetic field) can be expanded in multipoles of either electric (E) or magnetic (M) type. In this decay the photon carries away an amount of angular momentum $l\hbar$. The angular momentum $l\hbar$ depends on the angular momentum J of the levels involved in the transition. The type of multipole (E or M) on the other hand depends on the parity π of the levels that are involved. The change in parity for electric transitions is $\pi_E = (-1)^l$ while for magnetic transitions this is $\pi_M = (-1)^{l+1}$. For example in the transition from a 2^+ state to a 0^+ the photon carries away minimum $2\hbar$ angular momentum and does not change parity, the transition can thus be expanded in multipoles $E2$, $M3$, $E4$, $M5$ etc., the dominant term in this expansion is $E2$ [Kra88]. The transition strength of an $E2$ transition (denoted as $B(E2)$) depends on the detailed structure of the initial and final states involved and the probability of emission of the given multipole

$$B(E2 : J_i \rightarrow J_f) = \frac{1}{2J_i + 1} \langle \psi_f | E2 | \psi_i \rangle^2. \quad (1.5)$$

The matrix element $\langle \psi_f | E2 | \psi_i \rangle$ represents the coupling of the initial and final state by the $E2$ operator, and J_i and J_f are the spin of the initial and final state respectively. The transition strength is most often expressed in the Weisskopf unit (W.u.). The W.u. is

defined by $1 \text{ W.u.} = 5.94 \cdot 10^{-6} A^{4/3} e^2 b^2$, where b is the unit barn.¹⁰ One W.u. corresponds to a transition from $|j^2 J = 2\rangle$ to $|j^2 J = 0\rangle$ where two nucleons in orbital j change their coupling from a 2^+ state to a 0^+ state [Cas00]. The $B(E2: 2^+ \rightarrow 0^+)$ value of magic nuclei is approximately 5 W.u.. In nuclei far from magicity¹¹ $B(E2)$ values are high as they increase with increasing collectivity, and can range up to a few 100 W.u.. Note that neutrons can not directly contribute to the $B(E2)$ value as they are chargeless particles, but they do affect the $B(E2)$ value indirectly as they induce a polarization of the core. Together with the two neutron S_{2n} and two proton separation energy S_{2p} , the energy of the 2^+ state E_{2+} , the $B(E2)$ value is also related to magicity of nuclei and can give us more insight in nuclear structure.

1.3 The $N = 40$ Subshell in ^{68}Ni

One element in the periodic table of which the evolution of nuclear structure from the valley of stability to the neutron drip line¹² can be studied is nickel. Nickel has 28 protons and the number of neutrons ranges from 20 to 50, the nickel series ends with doubly magic nuclei at the boundaries, namely ^{48}Ni and ^{78}Ni . Hence a wide range of Z/N ratios can be investigated. There are five stable isotopes of nickel namely ^{58}Ni , ^{60}Ni , ^{61}Ni , ^{62}Ni and ^{64}Ni of which the first is the most abundant isotope, all other isotopes are radioactive and decay via β -decay. ^{78}Ni is a particularly interesting nucleus to study since $N = 50$ and $Z = 28$ are both magic numbers at least in the valley of stability [Lea05] and is an important nucleus in the theory of nucleosynthesis [Hea05]. In the r-process¹³ ^{78}Ni is an important *waiting point*¹⁴. Unfortunately experimental data are very scarce since ^{78}Ni is very exotic and hard to produce in nuclear reactions, on the other hand many theoretical calculations on the structure of ^{78}Ni have been done such as in [SN12] and [Cea12].

Besides ^{78}Ni there is another isotope that draws our attention namely $^{68}_{28}\text{Ni}_{40}$. In the shell model, ^{68}Ni has a closed proton shell configuration, 28 protons fill all energy levels up to and including the $\pi 1f_{7/2}$ orbital¹⁵. The energy gap between the $\pi 1f_{7/2}$ orbital and the next orbital ($\pi 2p_{3/2}$) is in the order of 3 MeV. This is a typical value of energy gaps for closed shells and sufficiently high to reduce particle excitations to the $\pi 2p_{3/2}$ orbital. The 40 neutrons fill all orbitals up to and including the $\nu 2p_{1/2}$ orbital. Although $N = 40$ is not a typical magic number, ^{68}Ni does show typical features of doubly-magic nuclei. Which will be discussed in the following.

¹⁰The unit barn b is equal to 10^{-28} m^2 and is often used as a unit of nuclear reactions cross sections. Transition strengths are often expressed in $e^2 b^2$.

¹¹Nuclei where nucleons occupy orbitals up to the middle of major shells, and the number of neutrons or protons lies in between two sequent magic numbers. For instance $^{160}_{66}\text{Dy}_{94}$ with $B(E2: 2^+ \rightarrow 0^+) = 194 \text{ W.u.}$ [Bea07a].

¹²The neutron dripline is the boundary of the nuclear chart in figure 1.1 on the neutron-rich side. At the boundary the neutron separation energy is less or equal to zero, and emission of a neutron is energetically favoured.

¹³The r-process is the rapid capture of neutrons. This process occurs in core-collapse supernovae where a high neutron flux makes it possible for nuclei to absorb many neutrons.

¹⁴At waiting-point nuclei in the r-process the reaction sequence halts to wait for the decay of the nucleus.

¹⁵Protons are referred to with the symbol π , neutrons with ν .

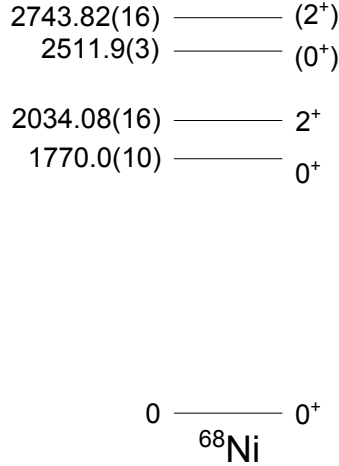


Figure 1.4: Low energy excited states of ^{68}Ni from [Mea12].

1.3.1 Excitation Energy

In 1982 the structure of ^{68}Ni was studied via a two-proton transfer reaction, $^{70}\text{Zn}(^{14}\text{C}, ^{16}\text{O})^{68}\text{Ni}$ [Bea82]. It was found that the first excited state is a 0^+ state at 1.77 MeV. This is already surprising since in most even- A nuclei the first excited state is a 2^+ state. The first 2^+ state in ^{68}Ni , denoted as 2_1^+ , was found at 2033 keV [Bea95]. The low energy excited states that have been observed to date are shown in the level scheme in figure 1.4.

This ordering of the 0_2^+ state and 2_1^+ has also been observed in doubly-magic nuclei such as ^{40}Ca and ^{16}O [Bea82]. Moreover also in ^{90}Zr with $N = 50$ and $Z = 40$ this ordering is observed. These observations indicate that $N = 40$ or $Z = 40$ may behave as a major closed shell, therefore ^{68}Ni is considered to be a *semi-magic* nucleus.

Not only the ordering of the 0_2^+ state and 2_1^+ state supported the idea of semi-magicity. When the energy of the 2_1^+ state of ^{68}Ni is compared to the neighbouring even- A nickel isotopes, as shown in figure 1.5a, it can be seen that there is a maximum at $N = 40$ and $N = 28$.

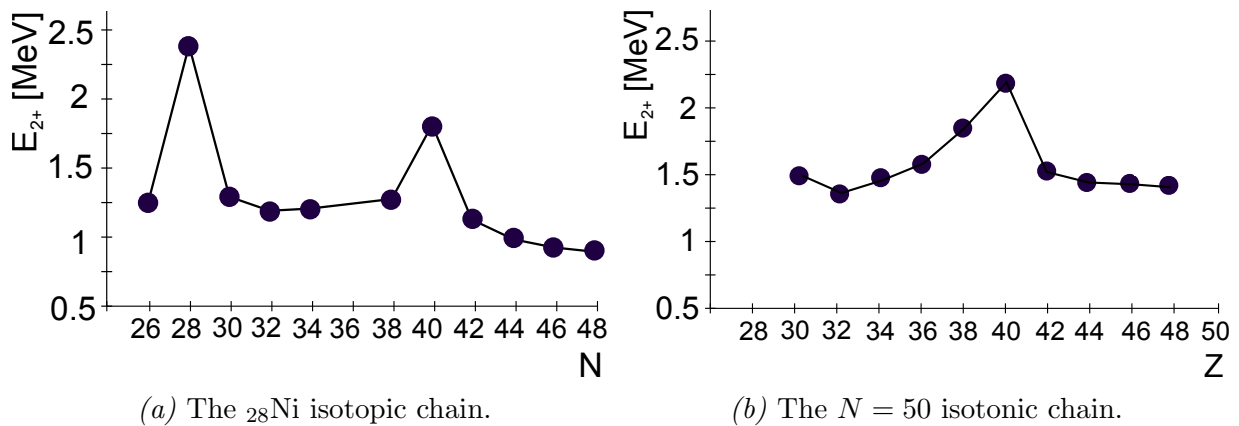


Figure 1.5: Experimental values of $E_{2_1^+}$ in the $Z = 28$ isotopic chain and the $N = 50$ isotonic chain [SP08].

Interestingly this feature is also observed in the even- A $N = 50$ isotones shown in figure 1.5b. In the latter the energy of the 2^+ state is highest at $Z = 40$.

It seems reasonable that $N = 40$ is restored as a shell gap in ^{68}Ni . It is known that proton-neutron residual interactions change the single-particle energy levels and can therefore change the gaps between shells [Oea01], [SP08]. Secondly for medium-mass neutron-rich nuclei, the surface consists of diffuse neutron matter, since the spin-orbit term is proportional to the derivative of the density, the spin-orbit term is weaker [Dea94]. This weakening of the spin-orbit interaction results in an increased energy gap at $N = 40$. As shown in figure 1.2, there is an energy gap at the occupation number 40 when the spin-orbit interaction is not taken into account.

On the other hand the high energy of the 2_1^+ can also be explained from parity considerations instead of assuming there is an energy gap at $N = 40$. Since the $1g_{9/2}$ orbital has positive parity and the $2p_{1/2}$ orbital has negative parity a particle-hole excitation¹⁶ (denoted as $1p - 1h$) from the $2p_{1/2}$ orbital to the $1g_{9/2}$ orbital results in negative parity states only. Hence to form a 2^+ state two particles have to be excited across the $N = 40$ gap (or the $Z = 40$ gap in the case of ^{90}Zr). Since this requires more energy the energy of the 2^+ state will be high. This change in parity of the levels across occupation number 40 originates from the solutions of a simple harmonic oscillator potential which have alternating parity.

1.3.2 $B(E2)$ Transition Probability

Besides the energies and ordering of the low excited state of ^{68}Ni , also the transition probability $B(E2 : 0_1^+ \rightarrow 2_1^+)$ is small compared to $B(E2)$ in neighboring isotopes. The $B(E2 : 0_1^+ \rightarrow 2_1^+)$ values in ^{68}Ni and neighbouring isotopes are shown in figure 1.6.

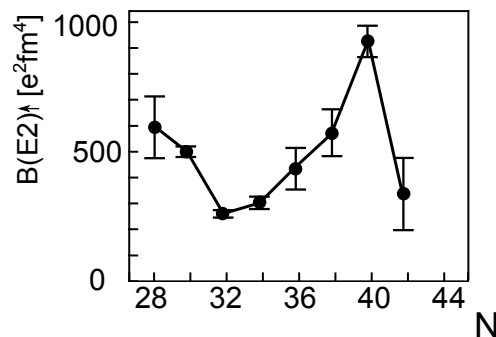


Figure 1.6: $B(E2 : 0_1^+ \rightarrow 2_1^+)$ transition strength values in the $_{28}\text{Ni}$ isotope chain. Values for $^{56-68}\text{N}$ are taken from [Rea01] and ^{70}Ni from [Pea06].

The $B(E2)$ of ^{68}Ni is $2.6(6) \cdot 10^2 \text{ e}^2\text{fm}^4$ or $3.2(7) \text{ W.u.}$ [Rea01] which is comparable to the doubly-magic nucleus ^{16}O with $B(E2) = 3.3(3) \text{ W.u.}$ [Sea02b]. Since a low $B(E2)$ value can indicate there is a low degree of collectivity, this measurement fits in the picture of a $N = 40$ as a (semi-)closed shell. On the other hand this can also be explained from parity considerations. The parity change in the fp and gd shell results in a lack of $E2$ excitations since $E2$ transitions conserve parity.

¹⁶One particle excitations leaving a hole in the initial orbital are called one-particle one-hole excitations, denoted as $1p - 1h$.

1.3.3 Separation Energy and β Decay Studies

Starting from the hypothesis of a semi-magic ^{68}Ni nucleus it is expected that the two-neutron separation energy S_{2n} is high at $N = 40$, corresponding to strongly bound neutrons in the $2p_{1/2}$ orbital. From mass measurement of the even- A nickel isotopes, S_{2n} has been deduced [Gea07, Rea07].

As can be seen in figure 1.7 the two-neutron separation energy of ^{68}Ni does not deviate from the decreasing trend of S_{2n} in the neighbouring isotopes. Hence the $N = 40$ configuration is not as energetically favored as is the case for major shell closures.

Moreover β -decay studies of ^{69}Ni and ^{69}Co showed that there are particle-hole excitations across $N = 40$ at low energies in ^{69}Ni and ^{69}Cu . This implies that the stabilizing effect of the $N = 40$ semi-magic shell gap rapidly decreases [Mea99]. For particle-hole excitation to occur at low energies either protons or neutrons have to be excited to a higher orbital easily. Since protons have a closed shell configurations it would seem that neutrons are excited to the $1g_{9/2}$ orbital. This would mean that the gap at $N = 40$ is small.

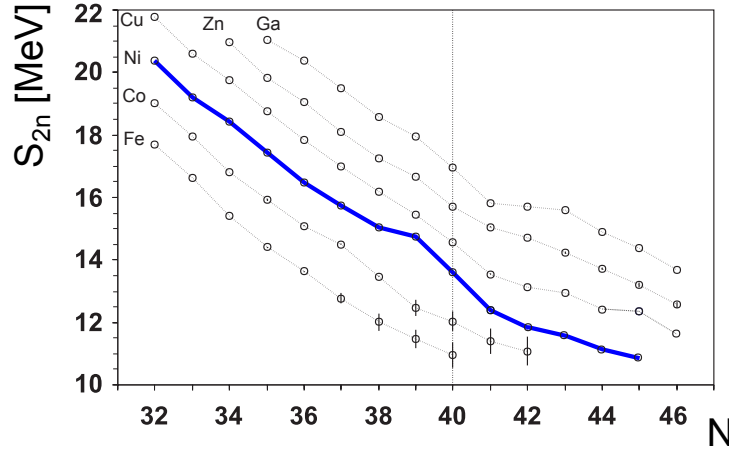


Figure 1.7: Two-neutron separation energies in the region of $28 \leq N \leq 50$ from measurements in ISOLTRAP [Gea07] and JYFLTRAP [Rea07].

1.3.4 Shell Model Calculations

Large scale shell model calculations¹⁷ of ^{68}Ni based on a ^{48}Ca core and active orbitals for the protons and neutrons can reproduce the experimental results [Sea02b]. The underlying microscopic structure of the model reveals that the low $B(E2: 0_1^+ \rightarrow 2_1^+)$ value can be explained by neutron pair scattering across $N = 40$. The $B(E2)$ value reflects a proton component in the wave-function, this value is reduced because the neutron amplitude increases due to pair scattering across $N = 40$ [Lea03]. The calculations show that the content of (p, f) neutrons in the wave function has a minimum at $N = 40$, which means many neutrons are occupying the $1g_{9/2}$ orbit instead of the orbits in the fp shell. Thus it is more favorable to excite two neutrons across $N = 40$ than one proton. These theoretical calculations point in the direction of a rather small gap between the $2p_{1/2}$ and the $1g_{9/2}$ orbitals allowing fluent pair scattering across $N = 40$.

Besides the 2^+ state also the 0^+ states in ^{68}Ni and in its valence counterpart ^{90}Zr with $Z = 40$ and $N = 50$ have been investigated. The first 0^+ state in ^{68}Ni lies at 1770 keV, shell model calculations show this is a $\nu(2p - 2h)$ state, where two neutrons are excited to the $1g_{9/2}$ orbital [Pea10]. The strong pairing interaction is responsible for the low energy of this state, and is consistent with a good shell closure at $Z = 28$.

In ^{90}Zr 0^+ excited states are found at 4126 keV and 5441 keV which are believed to be $\nu(2p - 2h)$ states [Pea10], so scattering across the magic shell $N = 50$ occurs. It is predicted that an analog $\pi(2p - 2h)$ state across the magic shell $Z = 28$ exists in ^{68}Ni . From the energy of the $\pi(1p - 2h)$ state in ^{67}Co and $\pi(2p - 1h)$ in ^{69}Cu state the energy of the $\pi(2p - 2h)$ state in ^{68}Ni was predicted to lie at 2202 keV [Pea10]. The reason that this intruder state¹⁸ has a low energy would be due to a strong attractive $\pi - \nu$ residual interaction. However this $\pi - \nu$ residual interaction can only be strong when many neutrons are available, thus that many neutrons reside across the $N = 40$ gap. Consequently $N = 40$ can not be the boundary of a closed shell, but there is a rather small energy gap between the $2p_{1/2}$ orbital and the $1g_{9/2}$ orbital. However, these predictions have not been confirmed experimentally, the predicted $\pi(2p - 2h)$ 0^+ state at 2202 keV has not yet been observed.

¹⁷In large scale shell model calculations as much orbitals as possible are considered as active orbitals. In these active orbitals nucleons can leave or excite to, for instance the $2p_{1/2}$ and $1g_{9/2}$ orbitals are considered as active orbitals, such that neutrons can leave the $2p_{1/2}$ orbital and go to the $1g_{9/2}$ orbital. The core consists of the lower lying filled orbitals where the nucleons are not affected by the residual interactions and the nucleons can not change their orbit. Ideally the core is taken as a doubly magic configuration.

¹⁸Intruder states are excited states in singly magic nuclei that originate from excitations across the major shell gap instead of from excitations of valence nucleons.

1.3.5 Transfer Reactions

Two neutron transfer reactions are known to be excellent probes to study $2p-2h$ states in medium-mass nuclei [Hea66]. In order to observe such a state in ^{68}Ni a transfer reaction experiment was performed at ISOLDE with a 2.6 MeV/A beam of ^{66}Ni and a target containing ^3H . The main aim of the experiment was to characterize the 0^+ and 2^+ states in ^{68}Ni via the $^{66}\text{Ni}(t,p)^{68}\text{Ni}$ two-neutron transfer in inverse kinematics. The analysis of this experiment is still ongoing. In addition the experiment allows to study the one-neutron transfer reaction $^{66}\text{Ni}(t,d)^{67}\text{Ni}$ by which the structure of ^{67}Ni can be explored [Pat08], [Rog10], this thesis will focus on the latter transfer reaction. In the extreme independent particle shell model, ^{67}Ni can be seen as ^{68}Ni with one hole in the $p_{1/2}$ orbital. As mentioned, this description works for nuclei with one nucleon more or less than doubly magic nuclei. Therefore the single-particle character of ^{67}Ni is a probe of the magic character of ^{68}Ni . One-nucleon transfer reactions are an often used technique to study the single-particle structure of nuclei. They offer a broad range of information on the structure. First of all one can explore the energies of the excited states from the decay of the populated states. Secondly since orbital angular momentum is conserved, the spin and parity J^π of excited states can be deduced from the angular distribution of the emitted particles. A third and final interesting quantity is the *spectroscopic factor*, this factor represents the purity of a state, in other words, to what extent a state can be described as a pure shell model configuration. A spectroscopic factor of 1 means that the observed state in ^{67}Ni is exactly the same as the initial nucleus ^{66}Ni plus one neutron in a particular shell model orbital. When the spectroscopic factor is lower than one, then the state is not a pure shell model state but for instance a mixture of different shell model configurations. Chapter 3 is dedicated to transfer reaction theory and how this can be used to investigate nuclear structure.

Chapter 2

Experimental Setup

2.1 CERN

The *European Organization for Nuclear Research* (CERN) is one of the most important research facilities in the world for the study of particle and nuclear physics. CERN was founded in 1954 as a joint venture of 20 European states. Today, scientists worldwide participate in international research programs. Thanks to this large co-operation, the most advanced detectors and accelerators in the world such as the Large Hadron Collider (LHC) could be built. The facility has expanded continuously during the last 50 years, new accelerators were constructed to reach even higher energies than before while the previous accelerators are used as injectors. In figure 2.1 the current accelerator complex of CERN is shown.

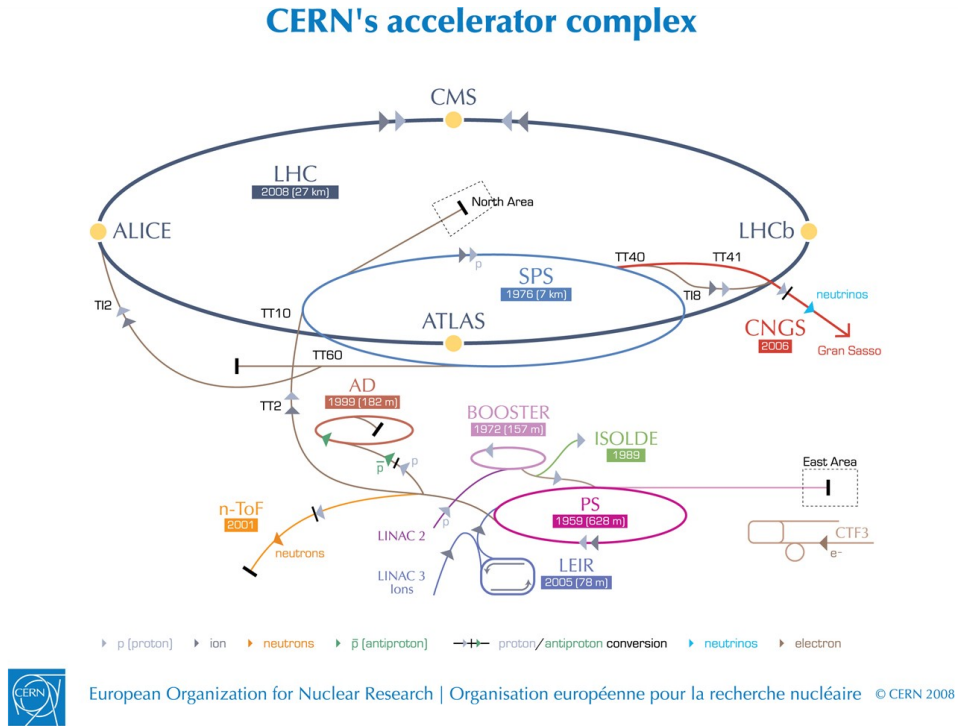


Figure 2.1: The CERN accelerator complex is a succession of accelerators that reach increasingly higher energies [CER08].

One of the facilities in CERN is dedicated to the production of a wide range of different nuclei, namely ISOLDE, an abbreviation of Isotope Separator On-Line. The $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ experiment described in this thesis has been performed at ISOLDE.

2.2 ISOLDE

The ISOLDE facility [Kug00] can be thought of as the alchemical factory of CERN. Up to 700 isotopes have been produced of more than 70 elements. It is located at the Proton Synchrotron Booster (PSB) as can be seen in figure 2.1, the layout of the experimental hall is shown in figure 2.2. In this section the main process of how ions are produced, selected and guided to the measuring stations will be described.

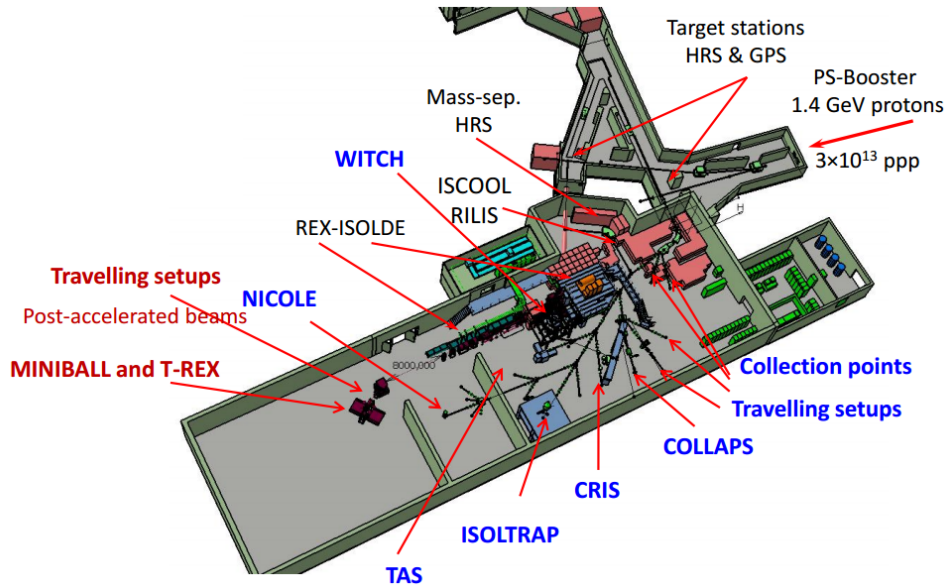


Figure 2.2: Layout of the experimental hall of the ISOLDE facility in CERN.

2.2.1 Isotope Production

In ISOLDE a wide range of nuclei are produced via spallation, fission or fragmentation reactions in a thick target. A pulsed beam of protons from the PSB with an energy of 1.4 GeV and an intensity of $1.6 \mu\text{A}$ impinges on the target material, each pulse contains about $3 \cdot 10^{13}$ protons. The target is a thick, solid, 50 g/cm^2 uranium carbide (UC_x) target. In the interaction of the beam with the target many different isotopes are produced, amongst them also ^{66}Ni , this isotope will be selected for this experiment. The produced isotopes diffuse and effuse out of the target that is held at a high temperature (about 2300°C) to enhance the speed of the diffusion. The speed of the diffusion or effusion depends on the type of element and on the specific materials of which the target container, the transfer line and the ion source are made of. One can shorten the release time of an isotope to a certain extent by increasing the temperature of the target. Short release times are very important in the production of beams of short lived radioactive isotopes. Once the diffused and effused atoms have left the target they are ionized. In ISOLDE three mechanisms can be operated to ionize the atoms: electron impact ionization in

high-temperature plasma sources, surface ionization and laser ionization in a hot cavity. Depending on the isotope one of the methods is best suited. The ^{66}Ni beam provided for this experiment was ionized by laser ionization.

2.2.2 RILIS

The laser ionization method is based on the fact that each element in the periodic table has its own “fingerprint”, namely the energy of the electronic energy levels. This information can be used to ionize one specific element in the mixture of diffused neutral atoms¹ and thus selects all atoms with a certain number of proton Z . Hence in addition to ionizing the atoms, the technique is also a first selection method. In RILIS (Resonant Ionization Laser Ion Source) [Mea93] two or three lasers, depending on the element, are fixed to the element-specific electronic transitions in the atom. This way a valence electron is stepwise excited until it has enough energy to escape the attractive Coulomb potential of the atom, in other words it is excited into the continuum. Figure 2.3 shows the ionization scheme for nickel. Ultimately an electric field extracts and accelerates the positively charged ions to 30 keV. In the case of nickel the ionization efficiency is up to 6% [web13].

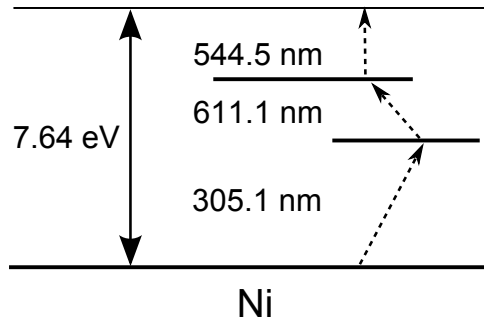


Figure 2.3: The ionization scheme for nickel as it is made use of at ISOLDE. Three lasers are fixed to specific energy levels to stepwise excite an electron to the continuum [Jea97, web13].

In this process not only the desired element can be positively charged. Elements that have a low ionization potential (like alkali elements) can also be ionized in the heated target by surface ionization. Consequently these ions will also be accelerated and contaminate the beam. The efficiency of surface ionization is $< 5\%$ [web13], it is clear that additional selection is necessary to further purify the beam and to select the ^{66}Ni isotope amongst all other nickel isotopes and the contamination. Therefore accelerated particles are guided to a mass separator.

2.2.3 Mass Separation

Mass separation is the second step in the selection process. In ISOLDE there are two mass separators, GPS (General Purpose Separator) and HRS (High Resolution Separator). In this experiment the GPS was used. This separator makes use of one bending magnet to

¹The hyperfine structure of the atomic levels is determined by the nuclear spin, it is therefore possible to produce isomeric beams, see e.g. [Vea04].

select isotopes with a certain A/q ratio, where q is the electric charge. By adjusting the magnetic field strength, nuclei with a certain A/q ratio can be selected. In this case the bending magnet lets particles with $A/q = 66$ pass through, while all undesired isotopes of nickel and other contamination are filtered out. Note that it is possible that the beam still contains contamination with similar A/q ratio. From here onwards, the beam with an energy of 30 keV can be sent to different detector setups in the experimental hall of ISOLDE. For this experiment the beam is sent to REX-ISOLDE.

2.3 REX-ISOLDE

REX-ISOLDE (Radioactive beam EXperiment at ISOLDE) [VR11] is a beamline in ISOLDE designed to study exotic nuclei via transfer reactions and Coulomb excitation. These type of methods however require higher beam energies than provided by ISOLDE. This section describes how the semi-continuous radioactive beam coming from the GPS is pulsed and post-accelerated in REX-ISOLDE. First the charge breeding system is discussed where the semi-continuous beam of singly positive charged ions from the GPS is manipulated. Secondly the post-acceleration with the linear accelerator is discussed. At the end an overview of the time structure of all components in REX-ISOLDE is given.

2.3.1 Charge Breeding System

The charge breeding system of REX-ISOLDE consists of three components. A Penning trap, where ions from GPS are collected and released in separate bunches. From now on the beam has a pulsed time structure, this is done to reduce the gamma background in the measurement. Secondly an electron gun to further ionize the ions to increase the acceleration in the linear accelerator. Finally the beam passes through another mass separator.

REX-Trap

REX-Trap is a Penning trap where ions from the semi-continuous beam of GPS are accumulated, bunched and cooled down by collisions with a buffer gas (argon or neon) and oscillating electromagnetic fields [Aea05]. The mass dependence of the electromagnetic cooling also provides a means to increase the purity of the beam. The trapping time is synchronized with the REX-EBIS time which will be discussed next.

REX-EBIS

In REX-EBIS (Electron Beam Ion Source) the ions are further ionized to higher charge states by means of electron stripping [Wea02], this technique has the advantage that it can be applied to further ionize any ion. In this process a beam of mono-energetic electrons is focused on the trapped ions, as a result the ions are stepwise ionized via electron impact. The centroid of the charge state distribution can be chosen so that it corresponds to the desired A/q ratio by adjusting the confinement time. The maximum A/q ratio that can be reached in REX-EBIS is 4.5 [Wen02]. The confinement time varies from 20 ms for light mass elements ($A < 40$) to over 200 ms for the heavy elements in the lead region ($A \leq 200$) [VR11]. In the case of ^{66}Ni the breeding time was 48 ms to produce a charge distribution

centered at the 17^+ charge state. The ions are released by adjusting the potential barrier of the trap. The efficiency of the combination of REX-EBIS and REX-TRAP (from GPS to the linear accelerator) is $0.098 \times 0.9 = 8.8\%$, respectively for ^{66}Ni .

Mass Separator

The purity of the beam has decreased drastically mainly due to the use of buffer gases in REX-Trap. To remove the contaminants the beam is sent through a mass separator which consists of an energy selective electrostatic deflector and a mass selective magnetic bender. Subsequently, the beam is sent to a linear accelerator.

2.3.2 Linear Accelerator

REX-ISOLDE is equipped with a linear accelerator [Sea02a] to increase the energy of the beam up to 3 MeV/u so that a wide range of nuclear reactions can be studied. In this experiment bunches of ^{66}Ni are accelerated to 2.6 MeV/u. This energy is needed to overcome the Coulomb barrier so that nuclear direct reactions, such as the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ transfer reaction, can take place. The transmission through the linear accelerator is 77% for $A/q = 3.882$ giving in total 7% transmission efficiency through REX-ISOLDE. Starting from a proton current of $1.6 \mu\text{A}$ in the PSB a ^{66}Ni beam was delivered to the Miniball + T-REX experimental setup every 51 ms.

2.3.3 Time Structure of REX-ISOLDE

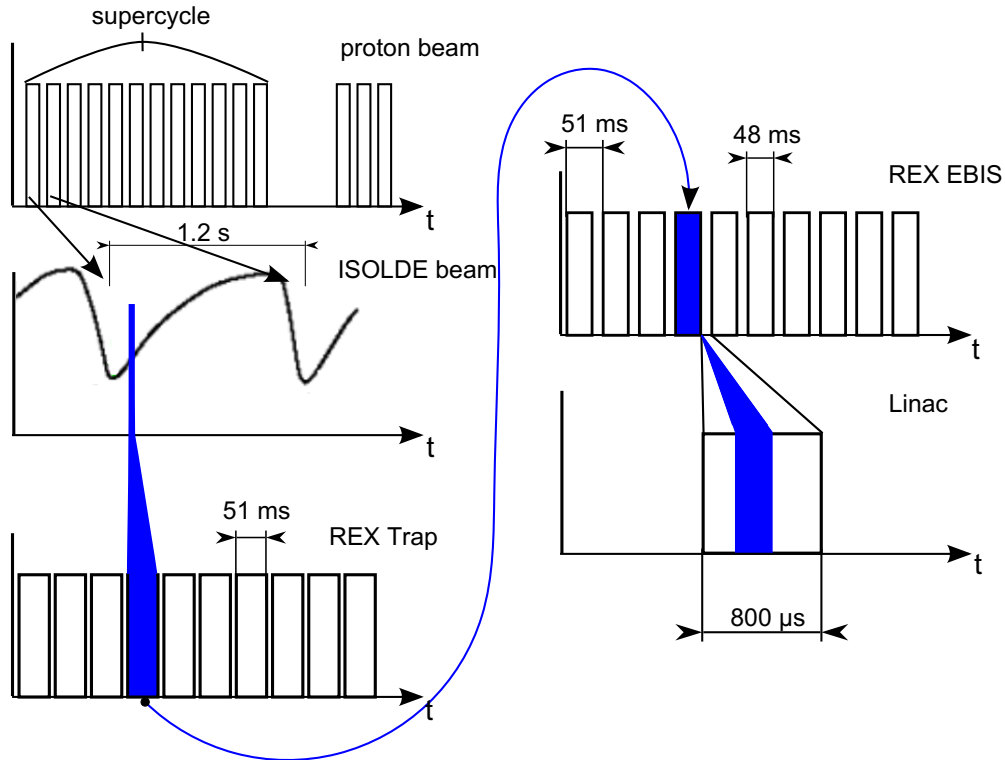


Figure 2.4: The time structure of the beam from the PS Booster to the target chamber.

In figure 2.4 the time structure of the beam as it goes from the PSB to the target chamber is shown. In the PSB storage ring bunches of protons are combined into one supercycle. Every 1.2 s or multiples of this period a pulse is delivered to ISOLDE [Lea97] where it impinges on the UC_x target. The synchronously produced reaction products diffuse out of the target and partially lose the discrete time-structure of the proton pulses. The delay incurred by the diffusion and effusion process results in a semi-continuous pulse shape. This time structure does not change as the beam passes through the GPS. In REX-Trap the beam is cooled and released in packages every 51 ms, the typical time width of the ion bunch is 10 μ s. The trapping time is determined by the charge breeding time in REX-EBIS. The charge breeding time of ^{66}Ni was 48 ms, resulting in an optimal ensemble of charged ^{66}Ni atoms centered around the 17^+ charge state. Subsequently 3 ms were used to release the particles, inject them into the mass separator and transport them to the linear accelerator. The typical time width of the ion bunch extracted from EBIS is 100 μ s [VR11]. The time width of the ^{66}Ni ion bunch however is 800 μ s, this mode of operation is referred to as *slow extraction*. In this mode the reactions of interest are more spread in time and the overlap of events in the detectors is lowered.

The opening window of the detectors is triggered by the EBIS pulse. In the span of 51 ms the detectors windows will be open for 1 ms when the beam hits the target, this window is called the ‘On Beam’ window. When the read-out and processing of the signals by the electronics is finished an ‘Off Beam’ window is opened for 1 ms, when there is no beam. The ‘Off Beam’ window serves to measure the background during the experiment. When the ‘Off Beam’ is closed nothing is measured until a new EBIS pulse arrives and the ‘On Beam’ window is opened again.

2.4 Target

For (t, d) and (t, p) transfer reaction in this experiment, a tritium loaded titanium target with a thickness of 500 $\mu\text{g}/\text{cm}^2$ is used. The target contains about 40 $\mu\text{g}/\text{cm}^2$ tritium and has an activity of 10 GBq. There are also some protons present on the level of a few percent. The target is mounted on a target ladder which can hold up to four targets, positioned in the center of the target chamber. A 2 kV voltage is applied over the target to reduce the number of electrons reaching the detectors and increase the signal-to-noise ratio.

2.5 Detection System

When a beam of ^{66}Ni at 171.6 MeV impinges on the target several nuclear reactions occur. The setup must be able to deal with this and identify different reaction products, specifically deuterons, protons, tritons, etc., so that in the end all different reaction channels of interest can be extracted and analysed separately. The type of detectors that are used in this experiment are the T-REX [Bea12] (“T” for Transfer) array of Si semiconductor diode detectors to detect charged particles and High Purity Ge semiconductor detectors in the MINIBALL setup [Wea13] to detect γ rays. A schematic view of the setup is shown in figure 2.5.

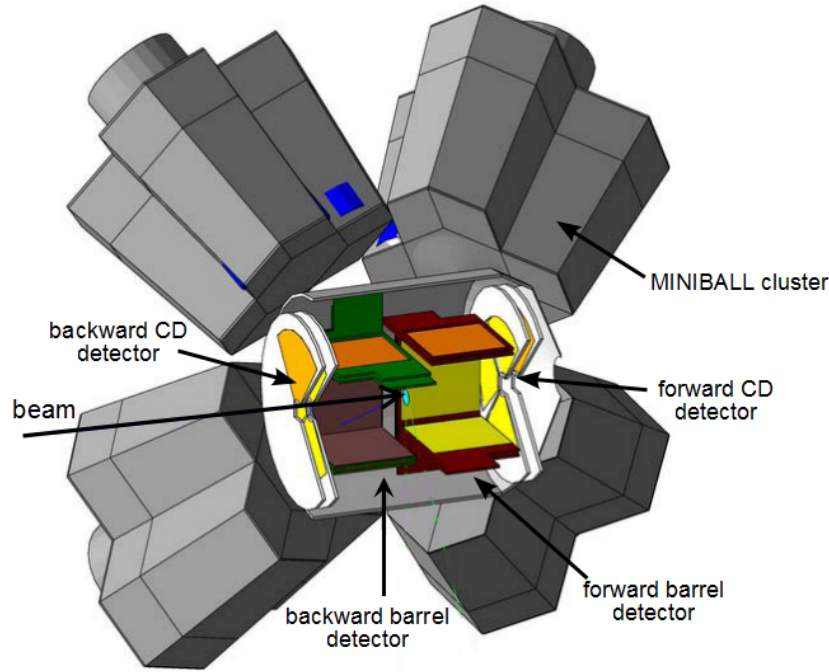


Figure 2.5: Schematic of the T-REX and Miniball setup at REX-ISOLDE. In total eight Miniball clusters surround the target chamber. Inside the target chamber two barrel detectors and two CD detectors are placed around the target [Bea07b].

2.5.1 T-REX Silicon Diode Detector Array

T-REX is a setup of silicon detectors optimized for the study of transfer reactions in inverse kinematics in combination with Miniball γ -detectors. Transfer reactions in inverse kinematics impose several requirements on the setup as described in [Bea12]. First of all the small polar angles of the beam-like ejectiles require the measurement of the recoils for a wide range of polar angles. Secondly the low intensity of the radioactive beam requires a highly efficient setup covering a large solid angle. The T-REX setup satisfies the mentioned requirements with a configuration consisting of two types of detector arrays: two barrel detectors and two CD-detectors on either side of $\theta_{\text{lab}} = 90^\circ$ as depicted in figure 2.5, the definition of the laboratory angles is shown in figure 2.6.

The RSSD² barrel detectors consist of four quadrants of 50×50 mm planar ΔE -E detectors assembled in a windmill shape. These planar ΔE -E detectors are composed of thin ($140 \mu\text{m}$) silicon detectors in front and a 1 mm silicon pad detector at the back. This telescope configuration is necessary to identify different types of particles from the energy loss in the ΔE -detector. The use of ΔE -E telescopes enables the identification of light particles, in this case especially protons, deuteron, tritons, alpha particles, ^3He , etc.. The ΔE -detectors are segmented in sixteen resistive strips, the strips are oriented perpendicular to the beam direction to allow to determine the angle of incidence as shown in figure 2.6. The position along a strip is determined by splitting the deposited charge in the resistive strip. The barrel detectors are placed at a distance of 29 mm from the beam axis. They cover 56% of the total solid angle, the gap at $76.5^\circ < \vartheta_{\text{lab}} < 100^\circ$ is due to the

²Resistive-Strip Silicon Detector

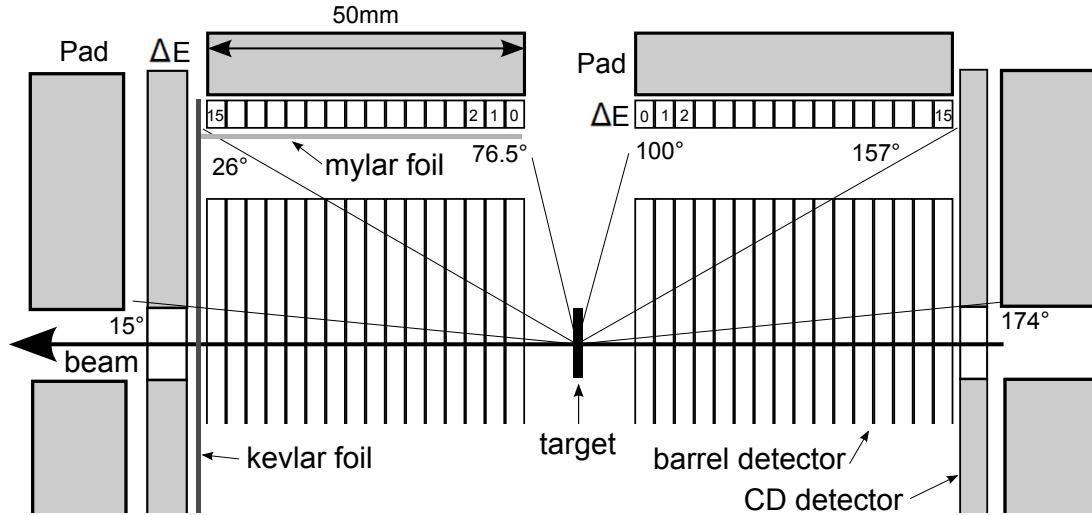


Figure 2.6: The angular coverage of the T-REX silicon detector array, the barrel detectors mostly cover the left, right, top and bottom of the chamber, the CD detectors cover the most forward and backward angles. The range of the angular coverage of the detectors is given in lab angles.

target ladder mounting. In front of the barrel detector in forward direction, a $11.57 \mu\text{m}$ thin MylarTM foil is placed to prevent high count rates from heavy elastically scattered particles, namely ^{66}Ni and titanium. Energetic light particles such as protons, deuterons and tritons easily pass through the foil without losing a lot of energy. For instance, a 10 MeV deuteron loses about 0.1 MeV in the Mylar foil. The use of this foil increases the signal-to-noise ratio because heavy scattered particles (from elastic scattering of ^{66}Ni on ^{48}Ti) are stopped in the foil at lab angles $\geq 60^\circ$. Unfortunately the use of this foil also reduces the energy resolution. For light particles the resolution is not as much affected as for heavy particles. In backward direction a foil is not necessary since in elastic scattering the particles cannot be emitted in backward direction. Only in inelastic scattering particles can be emitted in backward direction, for instance in a (t, d) transfer reaction, where the deuteron can be emitted in any direction.

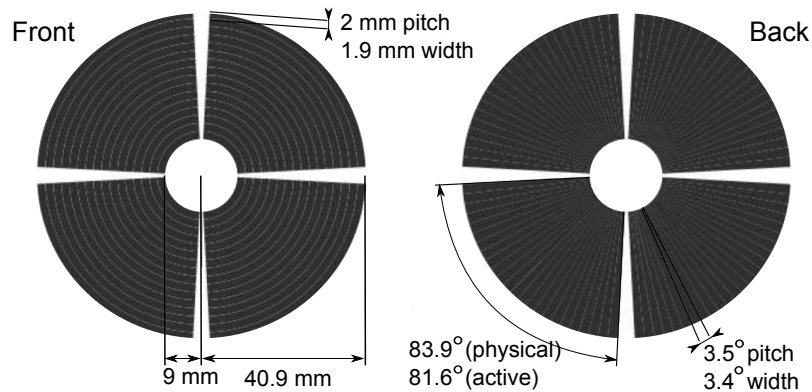


Figure 2.7: CD detector structure with 16 annular strips and 24 sector strips in each quadrant.

Table 2.1: T-REX silicon detector array specification for the $^{66}\text{Ni}(t, d)$ and $^{66}\text{Ni}(t, p)$ transfer reactions at REX-ISOLDE.

<i>Barrel Detector</i>				
Detector		Thickness [μm]	Segmentation	Foil
Forward	ΔE	140	16 resistive strips	11.57 μm , Mylar
	Pad	1000	-	
Backward	ΔE	140	16 resistive strips	-
	Pad	1000	-	
<i>CD Detector</i>				
Detector		Thickness [μm]	Segmentation	Foil
Forward	ΔE	500	16 annular rings, 24 radial strips	50 μm , Kevlar
	Pad	1500	-	
Backward	ΔE	140	16 annular rings, 24 radial strips	-
	Pad	1500	-	

Besides the barrel detectors there are two DSSSD³ CD-detectors, again on both sides of the target. The shape of these detector is similar to compact discs, therefore they are called CD-detectors. The CD-detectors also have a ΔE -E telescope configuration. The ΔE detectors are segmented on both sides to allow position determination. The front side of the ΔE detector is divided in 16 concentric circles and split in four quadrants, the back side consist of 24 radial strips as shown in figure 2.7. The pad detector that is positioned behind the ΔE detector is not segmented. Together with the barrel detectors about 66% of the total solid angle is covered. In front of the forward CD-detector a 50 μm Kevlar foil is placed to stop scattered particles (mostly ^{66}Ni) from reaching the forward CD-detector. The analog signals from each segment of the barrel silicon detectors are shaped, amplified and digitized by ADC modules. An overview of the silicon detector specifications is given in table 2.1.

2.5.2 Miniball HPGe Detector Array

The Miniball array [Eea01] is an array of eight cluster which are composed of three High Purity Germanium (HPGe) crystals, each cluster is cooled with liquid nitrogen down to 77 K. The crystals are six-fold segmented, individually encapsulated and tapered germanium crystals. The Miniball clusters surround the target chamber covering almost 70% of the total solid angle. In total 144 segments allow to determine the position of the incident gamma ray. This granulation allows to perform a Doppler correction on the spectrum and reduce Doppler broadening of γ -rays emitted by nuclei with velocities up to $0.07c$. In the analysis an add-back procedure is applied, summing up the γ rays that are simultaneously incident on crystals of the same cluster. This way one can correct for Compton scattering within the same cluster.

The signal produced in each segment is digitally analysed by DGF (Digital Gamma Finder) modules [XIA12]. The most important advantage of these digital modules is the fast signal processing. The FWHM (Full Width at Half Maximum) of a segment is

³Double-Sided Segmented Silicon Detector

energy dependent and in the order of a few keV.

2.5.3 Beamdump Detector

The ^{66}Ni beam and heavy reaction products with low emittance⁴ like ^{67}Ni and ^{68}Ni leave the target chamber through the hole in the center of the CD detector. The particles are stopped in a thick aluminum foil about 2 m away from the target chamber. Outside the beamdump chamber a single coaxial germanium detector is placed to detect γ rays from the particles implanted in the aluminum foil. The purpose of this detector is to measure the decay of isomeric states with a half life up to few μs . In the case of ^{67}Ni we are interested in the decay of the 1007 keV isomer with a half life of 13.3(2) μs [Gea98]. Ofcourse the detector will detect mostly γ rays from the β decay of ^{66}Cu to ^{66}Zn which originates from the β decay of ^{66}Ni which always populates the ground state of ^{66}Cu . To reduce the signals from the β which increases in time, the aluminum foil is replaced every 8 hours.

2.6 Efficiency of the Miniball Detectors

To determine the actual number of emitted γ rays with a certain energy, the energy-dependent absolute efficiency of the detector must be taken into account. This section is dedicated to how the efficiency of the Miniball detectors can be determined. The absolute efficiency of a detector is defined as

$$\epsilon_{\text{abs}}(E) = \frac{\text{Number of counts in the photopeak with energy } E}{\text{Total number of emitted } \gamma \text{ rays with energy } E}. \quad (2.1)$$

The intrinsic efficiency is defined as

$$\epsilon_{\text{int}}(E) = \frac{\text{Number of counts in the photopeak with energy } E}{\text{Total number of } \gamma \text{ rays incident on the detector surface with energy } E}. \quad (2.2)$$

Generally the intrinsic efficiency of a Ge detector is only a few percent and depends on the energy of the photons [Kno10]. For γ rays with an energy below 100 keV the intrinsic efficiency is almost 100% since the photoelectric absorption dominates, via this process the full energy of the photon can be absorbed in the detector material. However it is expected that the absolute efficiency drops fast for low energy gammas due to absorption in the aluminum capping of the Miniball clusters and the dead layer of the Ge semiconductor detector. For γ rays with energies over 100 keV the Compton effect plays an increasingly important role⁵. In Compton scattering photons interact with free electrons in the material and lose only a part of their energy. The γ rays still interact with the detector but some of them will not deposit their full energy in the detector volume. Gammas with energies over 1 MeV are even more likely to pass through the detector volume.

⁴The scattering angle must be sufficiently low such that the deflected particle is still implanted in the aluminum foil in the beamdump chamber.

⁵When the gamma energy is higher or equal to 1022 keV pair production can also occur.

The standard procedure to determine the efficiency of a Ge detector is to use a source that emits many γ rays over a relatively wide range of energies. The choice of sources for the efficiency calibration depends on the range of energies one wants to detect in the experiment. If one desires to detect low energy gammas and X-rays (< 100 keV) it is best to use sources that emit γ rays in this range. In the study of the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ reaction the γ rays of interest have energies from 300 keV to 4 MeV. The calibration sources that are used are ^{152}Eu and ^{60}Co . The half-life of the ground states of ^{152}Eu and ^{60}Co are respectively 13.5 y and 5.27 y. ^{60}Co decays to ^{60}Ni via β^- decay. ^{152}Eu undergoes β^- decay to ^{152}Gd (with branching ratio 27.9%) and β^+ /electron capture to ^{152}Sm in 72.1% of the cases. All daughter nuclei decay to the ground state mainly by the emission of γ rays. The energy and intensity of the most prominent γ rays of ^{152}Eu and ^{60}Co is given in table 2.2.

Table 2.2: Energy and absolute intensity per 100 decays of the most prominent gammas of ^{152}Eu [Coh96] and ^{60}Co [Tul03].

^{152}Eu			^{60}Co	
Energy [keV]	Intensity	Decay type	Energy [keV]	Intensity
121.7817 (3)	28.58 (6)	β^+/EC	1173.228 (3)	99.9736 (7)
244.6975 (8)	7.58 (2)	β^+/EC	1332.492 (4)	99.9856 (4)
344.2785 (12)	26.5 (4)	β^-		
367.78887 (16)	0.861 (5)	β^-		
411.1163 (11)	2.234 (4)	β^-		
443.965 (3)	3.15 (3)	β^+/EC		
688.670 (5)	0.857 (8)	β^+/EC		
778.9040 (18)	12.94 (2)	β^-		
867.373 (3)	4.25 (2)	β^+/EC		
964.079 (18)	14.61 (2)	β^+/EC		
1112.069 (3)	13.64 (2)	β^+/EC		
1299.140 (9)	1.623 (8)	β^-		
1408.006 (3)	21.01 (2)	β^+/EC		

There are several methods to calculate the absolute efficiency of the detectors. In this work three methods will be discussed, namely the sum-peak method [Kea03], the cascade method [Kes10] and the activity method.

A first step in any of these methods, is to determine the relative efficiency of each γ ray. This is done by dividing the total number of counts in the photopeak by the intensity of that γ ray (given in table 2.2). All photopeaks are fitted with a Gaussian function imposed on a background which is described by a step function and a linear function as in equation (2.3) where p_0 , p_1 , p_2 , p_3 , p_4 and p_5 are the fit parameters.

$$fit(E) = \underbrace{p_0 + p_1 \cdot E}_{\text{linear background}} + \underbrace{p_2 \cdot \exp\left(-\left(\frac{E - p_3}{\sqrt{2} \cdot p_4}\right)^2\right)}_{\text{Gaussian}} + \underbrace{\frac{p_5}{\left(1 + \exp\left(\frac{E - p_3}{p_4}\right)\right)^2}}_{\text{step background}} \quad (2.3)$$

The peak content is the integral of the Gaussian minus the background. The step function background is only introduced when necessary, for instance when the photopeak is situated on a Compton edge in the spectrum. Otherwise the background is solely described by a linear function.

In the analysis we make use of an *add-back* procedure to reduce Compton scattering effects and increase the detection efficiency at high energies. When a γ ray deposits its energy in more than one HPGe crystal in a Miniball cluster (containing 3 HPGe crystals) then the event is identified as two individual γ rays. This reduces the detection efficiency of high energetic γ rays. The add-back procedure will correct for this by summing the deposited energy of the crystals that fired in a Miniball cluster. In the analysis the Miniball cluster in which a first γ ray is detected is blocked from detecting another γ ray for $0.2 \mu\text{s}$. When this γ ray deposits energy in more than one crystal of this cluster then the energies are summed and the event will be correctly identified. The blocking is necessary to prevent the summing of two individual γ rays. To illustrate the effect of this procedure, the relative efficiency of γ rays from ^{152}Eu is shown in figure 2.8 the case the add-back procedure is used, and when it is not used.

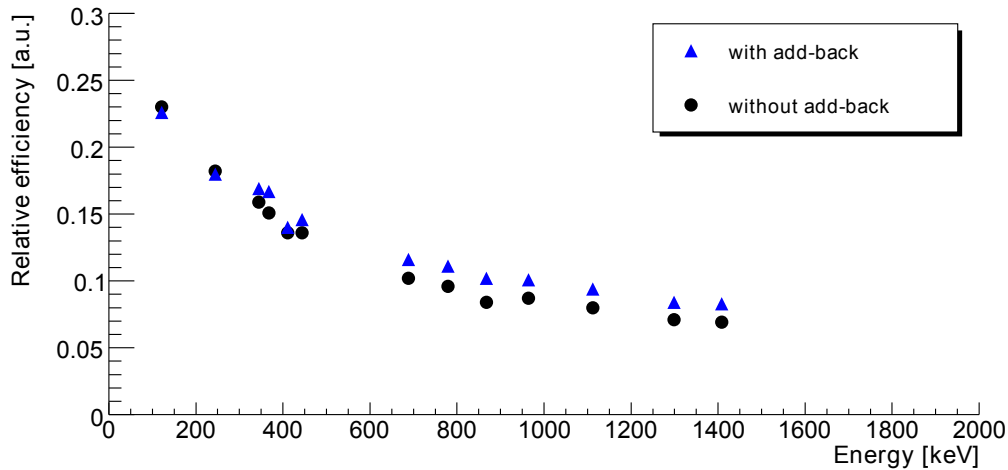


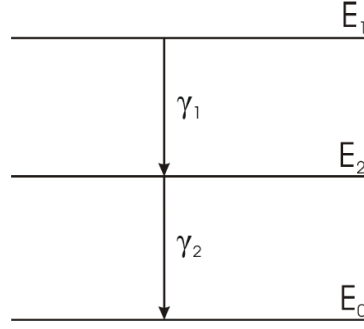
Figure 2.8: The relative efficiency of γ rays from ^{152}Eu with and without add-back procedure.

The efficiency is significantly higher at high energies when the procedure is used. At low energies < 200 keV the procedure slightly lowers the efficiency due to the blocking of the cluster. Overall the add-back procedure increases the efficiency in the energy region of interest. Therefore the add-back procedure will be applied.

2.6.1 The Cascade Method

A first method to calculate the absolute efficiency is the cascade method [Kes10]. In this method the absolute intensity is determined by examining γ rays in a cascade as shown in figure 2.9.

Nuclear excited states such as E_0 , E_1 and E_2 can be populated in β decay, in a nuclear reaction, via a γ transition or internal conversion from a higher lying level. Most often

Figure 2.9: Cascade of two γ rays γ_1 and γ_2

these excited states decay by emission of a γ ray. The typical lifetime of a γ decaying excited state is in the order of a few ps. Two γ rays such as in figure 2.9 can be detected in coincidence when the lifetime of energy level E_2 is short (less than the fixed prompt coincidence window that is used in the analysis, < 0.225 ns), in that case γ_1 will be followed by γ_2 . Thus when γ_1 is detected, γ_2 will also be emitted (in the case internal conversion does not occur). The opposite situation is not always true, i.e. when γ_2 is observed it is not necessarily so that γ_1 has been emitted. The detection of both γ rays in coincidence tells us something about the efficiency of the setup. For such a cascade the absolute detection efficiency of γ_1 can be calculated as follows:

$$\epsilon_{\gamma_1} = \frac{N_{\gamma_2\gamma_1}}{fN_{\gamma_2}I_{\gamma_1}} \sum_i^{E_2 \rightarrow \dots} (I_{\gamma_i}(1 + \alpha_{\gamma_i})). \quad (2.4)$$

The equation is similar for γ_2 . In this equation N_{γ_i} is the number of counts in the photopeak of γ_i , $N_{\gamma_2\gamma_1}$ represents the number of counts in the photopeak of γ_1 in coincidence with γ_2 , I_{γ_i} is the intensity of γ_i , α_{γ_i} represents the conversion coefficient of γ_i which is calculated with BrIcc [Kea08]. The summation runs over all possible ways to depopulate level E_2 , including γ_2 . The factor f is the ratio of active crystals of the Miniball setup. The latter is a correction factor that takes into account the fact that a single crystal cannot detect two coincident γ rays. Since when both γ rays are incident on the same crystal then the event will be seen as a single γ ray with an energy which is the sum of both γ rays. The spectrum will show a sum peak. The number of coincident γ rays in $N_{\gamma_2\gamma_1}$ are thus always detected by two different crystals. In this experiment there are 22 active crystals, 2 clusters with 2 active crystal, and 6 clusters with 3 active crystals. So the second γ ray from the cascade can only be detected in 21 of the 22 crystals, the factor f is then equal to $\frac{21}{22}$.

However in the analysis the add-back procedure is used, hence the whole cluster which detected the first γ ray is blocked. Consequently the second γ ray of the cascade can only be detected by one of the other clusters. In that case f is equal to $\frac{1}{22} \left(\frac{18}{22}(15+4) + \frac{4}{22}(2+18) \right) = 0.8719$.

In table 2.3 the cascades observed in the decay of ^{152}Eu and ^{60}Co are shown. For these γ rays the absolute efficiency is calculated with equation (2.4). The table also shows a scaling factor, this is the ratio of the absolute efficiency and the relative efficiency.

The absolute efficiency of the other gammas is calculated by multiplying their relative efficiency by the weighted mean of the calculated scaling factors. The result is shown in

Table 2.3: The absolute efficiency and scaling factor ($\epsilon_{\text{abs}}/\epsilon_{\text{rel}}$) calculated using the cascade method. The table shows the pairs of γ rays in a cascade from the decay of ^{152}Eu and ^{60}Co .

Source	Energy [keV]	Absolute efficiency [%]	Scaling factor []
^{152}Eu	121.8	13.8 (4)	0.609 (17)
	244.7	10.8 (3)	0.603 (17)
	344.3	10.4 (2)	0.616 (18)
	778.9	6.9 (2)	0.621 (19)
	344.3	10.5 (4)	0.620 (25)
	1299.1	5.1 (2)	0.612 (26)
			0.613 (8)
^{60}Co	1173.2	5.2 (1)	0.852 (22)
	1332.5	4.8 (1)	0.850 (23)
			0.851 (16)

figure 2.10. The absolute efficiency ranges from $\sim 14\%$ at 122 keV to $\sim 6\%$ at 1.4 MeV. The independent data from ^{60}Co and ^{152}Eu nicely agree.

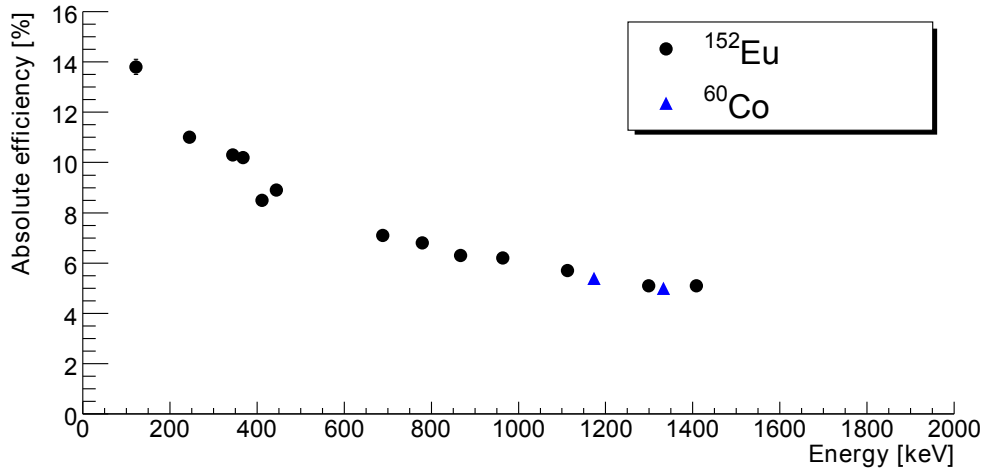


Figure 2.10: The absolute efficiency of the Miniball detector determined with the cascade method versus γ energy.

2.6.2 The Sum-peak Method

The sum-peak method [Kea03, Bea65] is based on the fact that coincident γ rays can deposit their energy in the same detector at the same time, creating a sum peak. From the number of summed γ rays and single γ rays the absolute efficiency of the setup can be extracted. The advantage of this method is that only one detector is needed while for the cascade method two detectors are necessary to measure coincidences. A second advantage of the sum-peak method is that it does not depend on the width of the time window that defines coincident γ rays in the analysis. For this method one usually uses a ^{60}Co source. The 1172.2 keV and 1332.5 keV γ rays are very intense and often detected

as a sum peak at 2.5 MeV.

The absolute efficiency of the photopeaks is given by:

$$\epsilon_{\text{photopeak}}(1.17 \text{ MeV}) = \frac{N(1.17 \text{ MeV})}{N_0 \cdot [1 - \epsilon_{\text{total}} \overline{W(0)}]} \quad (2.5)$$

$$\epsilon_{\text{photopeak}}(1.33 \text{ MeV}) = \frac{N(1.33 \text{ MeV})}{N_0 \cdot [1 - \epsilon_{\text{total}} \overline{W(0)}]}, \quad (2.6)$$

where N_0 corresponds to the total number of ^{60}Co decays and $\overline{W(0)} = 1.1$ to the effective angular correlation between the two γ rays [Kea03]. The formulas also contain the number of counts in a photopeak $N(E)$ and the total efficiency $\epsilon_{\text{total}}(E)$. The number of decays N_0 can be calculated as:

$$N_0 = \left[\frac{N(1.17 \text{ MeV}) \cdot N(1.33 \text{ MeV})}{N(\text{sum peak})} + N(\text{total}) \right] \cdot \overline{W(0)}, \quad (2.7)$$

where $N(\text{total})$ is the total number of counts in the spectrum (including the photopeaks, sum peaks, Compton area,...) [Bea65].

We assume that $\epsilon_{\text{total}}(1.17 \text{ MeV}) \approx \epsilon_{\text{total}}(1.33 \text{ MeV}) \approx \epsilon_{\text{total}}$, since the energies are similar and the efficiency does not strongly vary for energies over 800 keV. The total efficiency can then be calculated with the following equation:

$$\epsilon_{\text{total}} \approx \frac{1}{\overline{W(0)}} \left[1 - \sqrt{1 - \frac{N(\text{total})}{N_0} \cdot \overline{W(0)}} \right]. \quad (2.8)$$

Now ϵ_{total} can be inserted in equations (2.5) and (2.6) to calculate the photopeak efficiency.

This equation is derived for only one Miniball crystal since a sum peak can only occur in a single detector when the add-back procedure is not used. Thus the calculated efficiency corresponds to one crystal. The total absolute efficiency of the whole setup is then the sum of efficiencies of the individual crystals. Again by using the add-back procedure, one must consider the number of counts in the photopeak detected by one cluster instead of one crystal. The total efficiency of the setup is then sum of the efficiencies of each clusters. The absolute efficiency of the 1.17 MeV and 1.33 MeV γ rays from the sum-peak method together with the data from the cascade method is shown in figure 2.11.

The data from the sum-peak method agree well with the data from the cascade method. They do lie slightly higher than in the cascade method. One reason of this small discrepancy may originate from the way $N(\text{total})$ is defined. $N(\text{total})$ is the total number of counts in the spectrum (including the photopeaks, sum peaks, Compton area) [Bea65]. In the measured spectrum however there is background from other sources than ^{60}Co . For instance the constant background in the experimental hall, e.g. from ^{40}K and ^{208}Bi .

2.6.3 Efficiency from the Source Activity

A third, and most straightforward method to calculate the absolute efficiency is the activity method. This method is based on the fact that one can calculate the number of

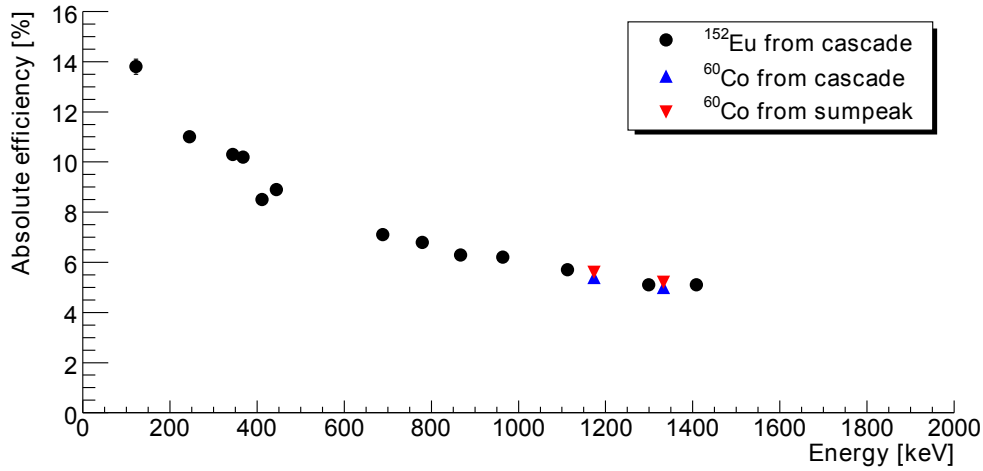


Figure 2.11: The absolute efficiency points from the cascade method and the sumpeak method.

emitted gammas from the activity A of a source. The absolute efficiency is

$$\epsilon_{abs}(E) = \frac{N(E)}{I_{\gamma}(E)A\Delta t}, \quad (2.9)$$

where $N(E)$ is the total number of counts in the photopeak with energy E , Δt is the total measurement time, and $I_{\gamma}(E)$ is the γ ray intensity. The activity of the ^{152}Eu and ^{60}Co source is 19.56 kBq and 23.03 kBq respectively. The obtained absolute efficiency is shown in figure 2.12.

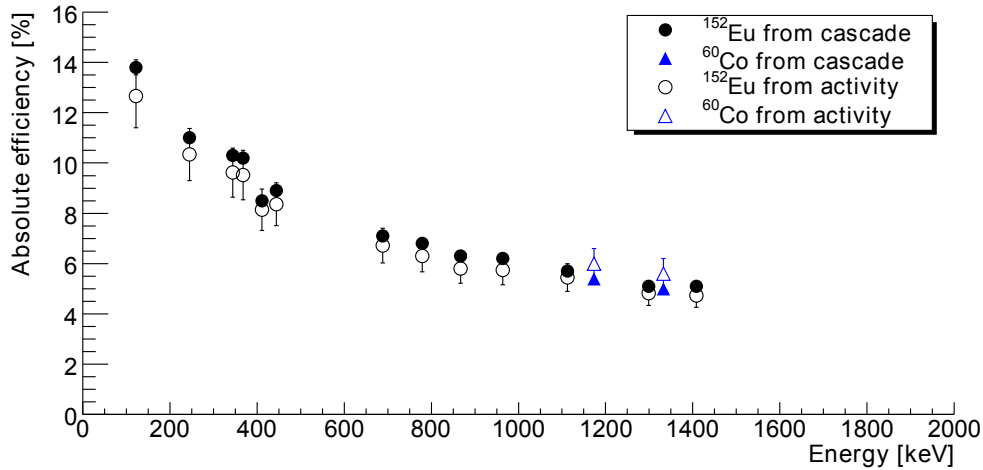


Figure 2.12: The absolute efficiency calculated using the source activity (empty circles and triangles) and using the cascade method (filled symbols).

The ^{152}Eu data points from the activity method lie lower than the cascade method data. For ^{60}Co the activity method gives a higher efficiency than the cascade method. Unfortunately the error on the activity of the sources is unknown, in figure 2.12 the error bars incorporate the error on the runtime, the peak content and an artificial 10% error on the

activity. Comparison with the cascade method (figure 2.12) indicates that the activity of the ^{152}Eu may be lower than 19.56 kBq while the activity of ^{60}Co is higher than 23.03 kBq.

2.6.4 The Efficiency Curve

To be able to evaluate the efficiency for any value of energy the efficiency points are fitted with an analytical function. We will use the data from the cascade method since the independent data from ^{152}Eu and ^{60}Co follow the expected decreasing trend, moreover the sum-peak method confirms the obtained absolute efficiency. The analytical function to describe the efficiency is:

$$\epsilon = \exp \left[a_0 + a_1 \ln\left(\frac{E}{x}\right) + a_2 \ln\left(\frac{E}{x}\right)^2 + a_3 \ln\left(\frac{E}{x}\right)^3 \right] \quad (2.10)$$

with fit parameters a_0 , a_1 , a_2 and a_3 . The energy in equation (2.10) is scaled with a factor x . This scaling is introduced to reduce the error on the fit parameters a_i . In the case of a linear function the error on the slope and offset can become quite high when the zero-point ($E = 0$) lies far from the data points. In that case, the problem is solved by taking $(E - x)$ as the origin, where x is the weighted average of the data points. When fitting a set of logarithmic points as in equation (2.10), the zero-point shift becomes $\ln(E) - \ln(x) = \ln\left(\frac{E}{x}\right)$. In figure 2.13 the relative error of the fit versus energy for different values of x is shown.

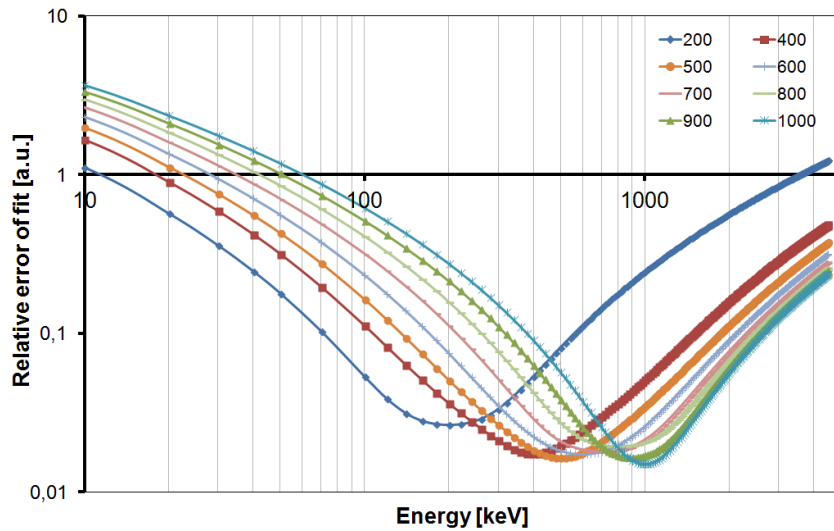


Figure 2.13: On the vertical axis the relative error of the function fitting the absolute efficiency is shown for different values of x (see equation (2.10)). On the horizontal axis the energy is shown.

The optimal value of x is chosen keeping in mind that the γ energies of interest in the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ transfer reaction, lie between 300 keV and 4 MeV. Therefore the absolute efficiency will be fitted with function (2.10) with $x = 800$. In figure 2.14 efficiency curve for $x = 800$ is shown.

The error on the absolute efficiency at low energies is large due to two reasons, first of all the absence of data points below 100 keV, secondly the choice of x . In the energy

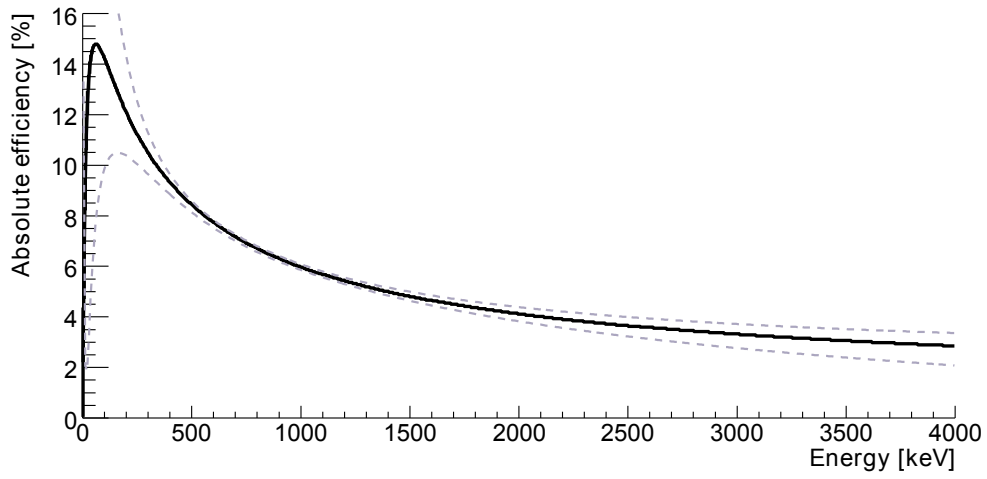


Figure 2.14: The absolute efficiency function from equation (2.10) fitted to the data from the cascade method with add-back procedure, the error on the efficiency is shown by the dotted lines.

region from 300 keV to 4 MeV the error on the fit is sufficiently small and can be used to estimate the γ detection efficiency.

Chapter 3

Transfer Reaction Theory

Nuclear reaction experiments are an important technique in the study of nuclear structure. As mentioned in chapter 1 the arrangements of the nucleons in ^{68}Ni is a particularly interesting case. The shell model offers a means to describe the level structure of this nucleus but experimental data are necessary to test these predictions. For this purpose, transfer reactions have been the standard procedure for examining the single-particle structure of nuclei. The theoretical model that is most used to describe transfer reactions is the distorted-wave Born approximation (DWBA) transfer theory. This chapter starts with an introduction to nuclear reactions with a focus on direct reactions, in particular transfer reactions. Next the general framework of scattering theory is presented, followed by notes on the optical model and the DWBA theory. The sections in this chapter are based on the book of Satchler G.R. [Sat90] on reaction theory, more in depth information can be found in [TN09] and [Sat83].

3.1 Terminology and Kinematics of Nuclear Reactions

3.1.1 Nuclear Reactions

In a typical nuclear reaction a projectile a is accelerated and interacts with a target nucleus A , which usually is at rest. The products of the reaction are the recoiling nucleus B and the ejectile b . This can be written as:

$$a + A \rightarrow B + b.$$

An alternative way of presenting the same reaction is $A(a,b)B$. Each possible combination of outgoing particles is called a *partition*. The particles in the partition $b + B$ can both be in their ground state or for instance B can be in an excited state. Therefore each partition is further distinguished by the state of excitation of each nucleus, such a pair of states is called a *channel*. To refer to a general class of reactions one uses the notation (a,b) , for example (t,d) which represents a stripping reaction where one neutron is transferred from ^3H to the target nucleus leaving ^2H as the ejectile.

In a nuclear reaction mass is not always conserved¹, the mass of the products can be lower or higher than the initial mass. The energy that is released or absorbed by the reaction is

¹only in elastic scattering.

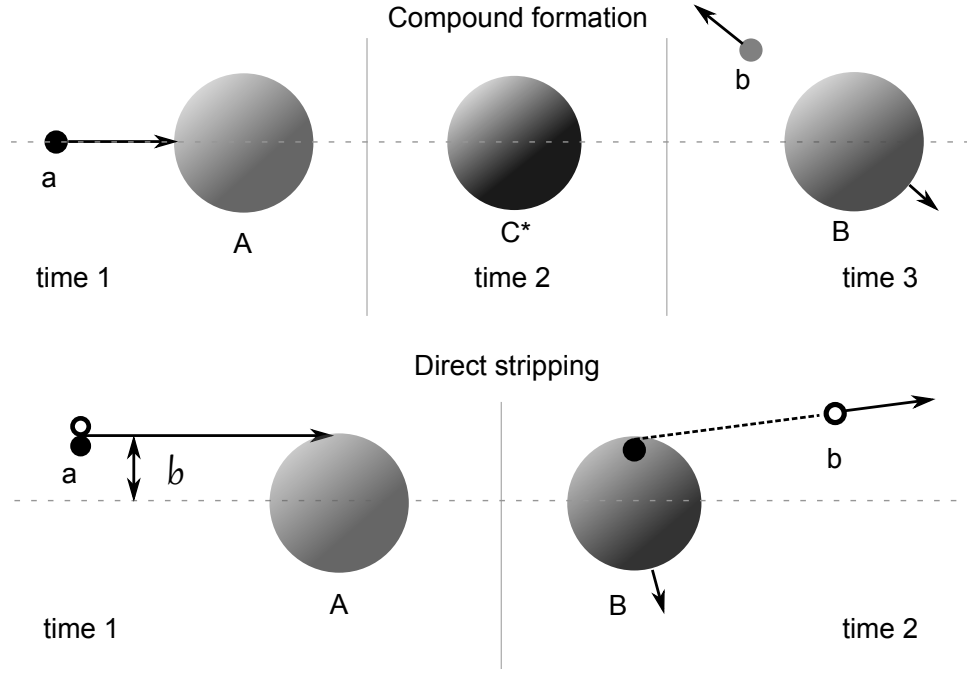


Figure 3.1: The top figure shows the mechanism of a compound nuclear reaction where a head-on collisions results in the formation of a compound nucleus C^* which decays by particle emission. The bottom figure shows a direct stripping reaction, one nucleon is transferred from the projectile to the target.

called the reaction Q value and is defined as the initial mass energy minus the final mass energy:

$$Q = (m_X + m_a - m_Y - m_b)c^2 \quad (3.1)$$

Reactions with a positive Q value are called *exoergic* reactions, in these reactions energy is released. When Q is negative the reaction is *endoergic* and an energy input is needed to initiate the reaction. To initiate an endoergic reaction the kinetic energy of the particles must be high enough such that the centre-of-mass (CM) energy is greater than Q . The Q value is an important parameter in nuclear reactions. In spectroscopy studies high Q reactions often are preferred since high excited states of the reaction products can be populated. When particle B in the reaction channel is in an excited state the Q value of the reaction is defined as Q_{ex}

$$Q_{ex} = (m_A + m_a - m_{B^*} + m_b) \quad (3.2)$$

$$= Q - E_{ex}. \quad (3.3)$$

The ejectile b can also be left in an excited state, we will however not consider this and limit the discussion to the cases where only B can be excited.

Nuclear reactions can be classified by means of the reaction mechanism, one discriminates *direct* or *peripheral* reactions and *compound* reactions.

Compound nuclear reactions are two-step processes and can occur when the impact parameter b is significantly smaller than the radius of the target nucleus R . A schematic

presentation of this process is shown in figure 3.1. The particles a and A merge together and form a compound nucleus C^* . In the compound nucleus the absorbed energy is distributed over all nucleons. This nucleus is usually in a very high energy state and mostly decays by nucleon emission to $B + b$ (or via β or γ decay). It is also possible that more than one particle is emitted. The time scale of this process is 10^{-15} s, which is slower than for direct reactions, since all nucleons are involved in the reaction.

Direct reactions are one-step processes and take place at the surface of the target nucleus, more quantitatively, when the impact parameter b is close to the nuclear radius. When only one or a few nucleons are transferred from the light particle (usually the incoming particle) to the target nucleus (*stripping*) or from the target to the projectile (*pick-up*) then the direct reaction is called a *transfer* reaction. When the light incident particle kicks out one or a few nucleons from the target the reaction is called a *knock-out* reaction. Since only a few nucleons at the surface are involved the reaction time is in the order of 10^{-22} s. The outcome of a direct reaction depends intimately on the way it is initiated [Sat90]. It is important to recognize that compound and direct reactions are not mutually exclusive, both types of reaction may contribute to a particular final state. In general direct reactions become more important as the energy of the incoming particle increases, at about 10 MeV direct reactions start to dominate. The relative importance also depends on the type of reaction, for instance a (p, d) reaction proceeds predominantly through the direct mode since the proton does not have to penetrate the Coulomb barrier.

The way particles b and B are emitted in direct and compound reactions is different. First of all there is a difference in the angular distribution of the particles. The angular distribution of evaporated particles from a compound reaction exhibits a forward and backward symmetry and does not vary strongly with angle. The angular distribution from a direct reaction is forward peaked and can vary strongly with angle. Later in this chapter it will be shown that the shape of this distribution is related to the spin and parity of the nuclear state that was populated.

Secondly the energy distribution of the evaporated particle b from a compound reaction will reflect a Maxwell-type distribution of nucleon velocities and peaks at low energies. The energy of the outgoing particles b from a direct reaction on the other hand show distinct peaks at high energies corresponding to the excited states of B . The energy spectrum of inelastically scattered α particles on Sn nuclei at different angles is shown in figure 3.2.

Another important difference is that the outcome of compound reactions is independent of how the compound nucleus was created. In other words, the compound nucleus has lost memory of the entrance channel $A + a$ by which it was formed. Figure 3.3 shows the cross section² of different reaction channels of compound reactions with different entrance channels. One can see that the excitation spectrum of the $^{60}\text{Ni}(\alpha, n)^{63}\text{Zn}$ reaction channel is nearly the same as the $^{63}\text{Cu}(p, n)^{63}\text{Zn}$ reaction. This indicates that the decay of the compound nucleus ^{64}Zn is independent of how it was formed.

In direct reactions the outcome of the reaction depends intimately on the way it is initiated. The cross section of the exit channel $b + B$ strongly depends on the entrance channel, i.e. on the overlap of the initial and final wave functions. The fact that the outcome of a direct reaction depends strongly on the entrance channel makes them an

²The cross section is a measure of the probability of an event to occur.

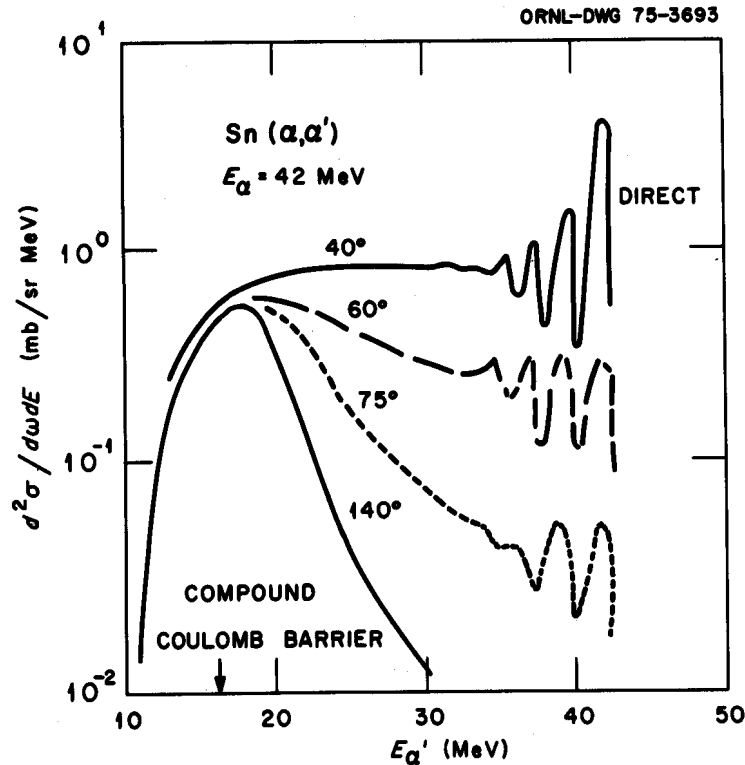


Figure 3.2: Energy spectra of α particles inelastically scattered from Sn nuclei at various angles after [Ce71]. The low energy α particles from compound nuclear reactions are almost isotropically distributed and have a Maxwell-type energy distribution. The high energetic α particles from direct reactions are forward peaked and show distinct peaks corresponding to low energy excited states of Sn. The peak with the highest energy corresponds to elastic scattering.

important technique to study nuclear structure. Later in this chapter we will show what information can be obtained from transfer reactions.

3.1.2 Kinematics of the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ Reaction

In most cases, the projectile is lighter than the target nucleus since it is easier to accelerate. In this case however, the target nucleus is ^3H , the projectile is ^{66}Ni , the ejectile is ^2H and the recoiling nucleus is ^{67}Ni , in short $^3\text{H}(^{66}\text{Ni}, ^{67}\text{Ni})^2\text{H}$. When the projectile is heavier than the target and the nucleus of interest is the ejectile, one refers to the reaction as a reaction in *inverse kinematics*. Mathematically they are identical when written in centre-of-mass coordinates³. In figure 3.4 one can see how the laboratory and centre-of-mass angles and vectors are related to one-another.

The experiment is performed with a ^{66}Ni beam since it is impossible to produce a target containing a sufficient amount of ^{66}Ni because this is an exotic nucleus which undergoes β^- -decay with a half-life of 54.5 h. At ISOLDE radioactive beams can be produced (see chapter 2). A target containing tritium ($t_{1/2} = 12.32$ y) can be manufactured. Even

³In the centre-of-mass coordinate system the origin is taken as the centre-of-mass such that $\sum_i m_i(\mathbf{r}_i - \mathbf{R}) = 0$, where $\mathbf{R}$ is the coordinate of the centre of mass [Sat90].

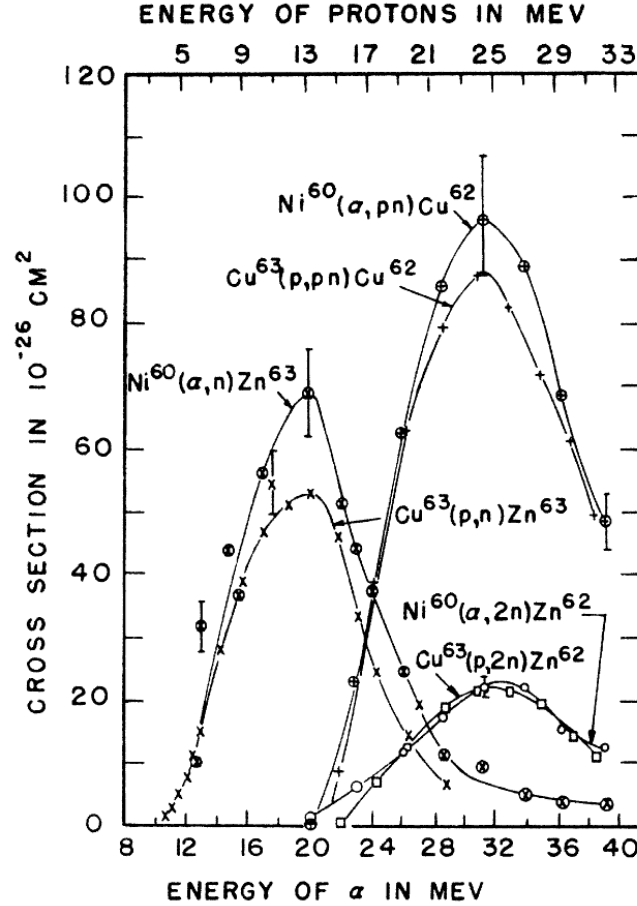


Figure 3.3: This figure shows the cross section of compound reactions of different reaction channels studied in [Gos50]. The excitation spectrum of a particular exit channel is independent of the entrance channel.

though the reaction is performed in inverse kinematics, it is custom to represent the reaction as ${}^{66}\text{Ni}(t, d){}^{67}\text{Ni}$. The Q value of this reaction is -0.45 MeV, the ${}^{66}\text{Ni}$ projectile is accelerated to 171.6 MeV, in the centre-of-mass frame the energy of the relative motion of the particles is 7.5 MeV. There is thus sufficient energy available to overcome the Coulomb barrier (6.1 MeV⁴) and to initiate the transfer reaction. There is $E_{\text{CM}} + Q = 7.05$ MeV available to leave ${}^{67}\text{Ni}$ in an excited state.

In the following, the kinematics of the reaction products of the ${}^3\text{H}({}^{66}\text{Ni}, {}^{67}\text{Ni}){}^2\text{H}$ transfer reaction will be discussed. The calculations were done with the transfer reaction kinematics program CATKIN [Cat04].

Figure 3.5a shows the relation between the laboratory angles and the the CM angles of the recoiling nucleus ${}^2\text{H}$ and the ejectile ${}^{67}\text{Ni}$.

The small deflection of the ${}^{67}\text{Ni}$ ejectile is demonstrated by the low maximal lab angle which is only about 2.1° . On the other hand, the light recoiling nucleus can be scattered in all possible directions in the lab frame.

In figure 3.5b the lab energy of both ${}^2\text{H}$ and ${}^{67}\text{Ni}$ versus the CM angle of ${}^2\text{H}$ is shown. In the CM framework there is a one-to-one relation between lab energy and the CM angle.

⁴The Coulomb barrier is calculated as $\frac{Z_1 Z_2 e^2}{R_1 + R_2}$, with $R_i = 1.2 A_i^{1/3}$.

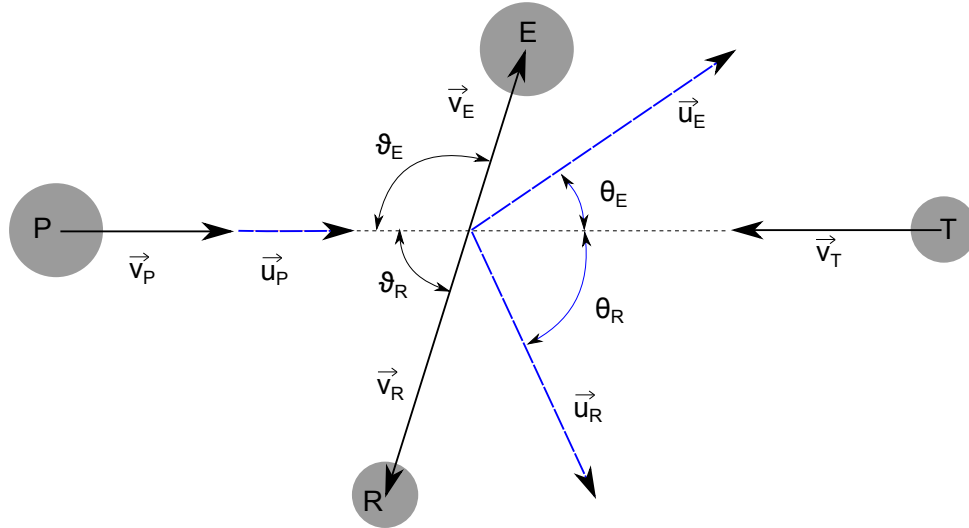
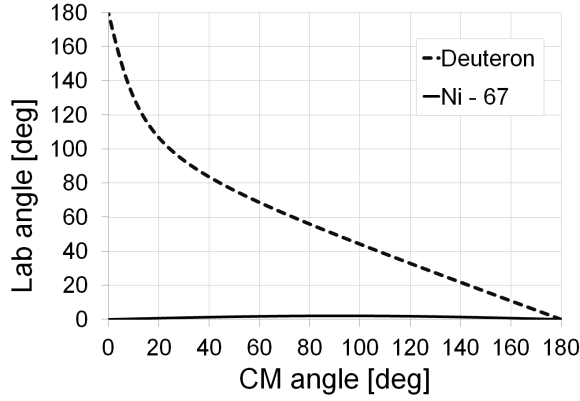


Figure 3.4: Angles and velocities in the laboratory (Lab) and the centre-of-mass (CM) frame. Vectors $\vec{u}$ and angles θ correspond to the lab reference frame. Vectors $\vec{v}$ and angles ϑ correspond to the CM reference frame. Capital letters P, T, R and E represent the projectile, the target, the recoiling nucleus and the ejectile.

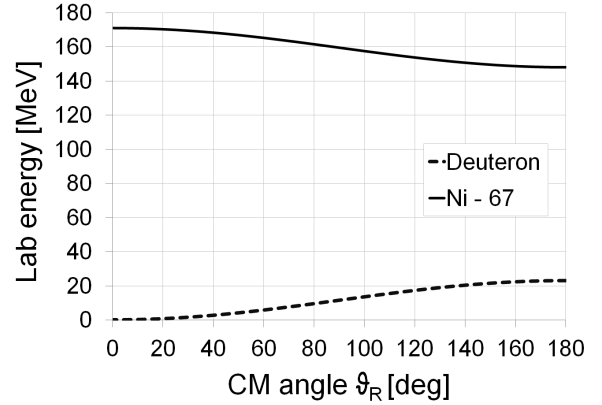
The energy provided by the incoming beam is converted in kinetic energy of the CM frame itself and the relative motion of the particles. After the collision or reaction the energy of the motion of the CM frame will be unchanged while the energy of the relative motion of the particles can change. The energy can be redistributed over the ejectile and the recoiling nucleus. This energy redistribution can be seen in the CM energy of the reaction products and of course also in the lab energy. The lab energy of the target-like particle (^2H) in figure 3.5b gradually increases with increasing CM angle ϑ_R , hence the ejectile (^{67}Ni) energy must decrease as ϑ_R increases.

Figures 3.5a and 3.5b can be combined to plot the lab energy versus the lab angle, this type of plot is called the *plectrum* plot of a reaction. Figure 3.6 shows parts of the plectrum plot focused on the deuteron and ^{67}Ni . Two transfer reactions have been considered, a transfer reaction to the ground state of ^{67}Ni (solid line) and to a fictitious state at 2 MeV (dotted line).

In the plectrum plot in figure 3.6c one can see that for each lab angle θ_E of ^{67}Ni except for $\theta_E = 2.1^\circ$ there are two possible lab energies. Consider the two extreme cases at $\theta_E = 0^\circ$. The case when the energy of ^{67}Ni is minimal corresponds to the situation where ^{67}Ni is back scattered in the CM frame and $\vartheta_E = 0^\circ$. The deuteron will have gained a lot of energy and is emitted in forward direction in the CM frame, corresponding to $\vartheta_R = 180^\circ$. In this collision the deuteron will have maximum energy and the ^{67}Ni energy will be minimal. The lab angle of the deuteron is then $\theta_R = 0^\circ$. The other extreme case where the ^{67}Ni energy is maximal corresponds to the CM situation where $\vartheta_E = 180^\circ$, here ^{67}Ni moves forward in the CM frame and the recoiling nucleus ^2H was emitted in the backward direction in the CM frame ($\vartheta_R = 0^\circ$). The energy of the deuteron will be minimal, which is indeed the case as can be seen in figure 3.5b at ($\vartheta_R = 0^\circ$) or at large lab angles in figure 3.6a. The deuterons emitted at low CM angles are of most interest to study ^{67}Ni . In this region one is most sensitive to the nuclear structure since the interaction occurred at the

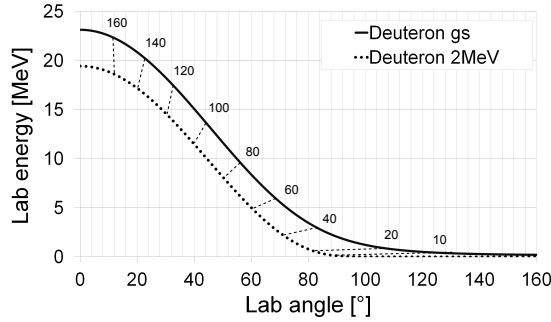


(a) Centre-of-mass angle versus laboratory angle of recoiling nucleus ^2H (dashed line) and ejectile ^{67}Ni (solid line) from the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ transfer reaction to the ground state.

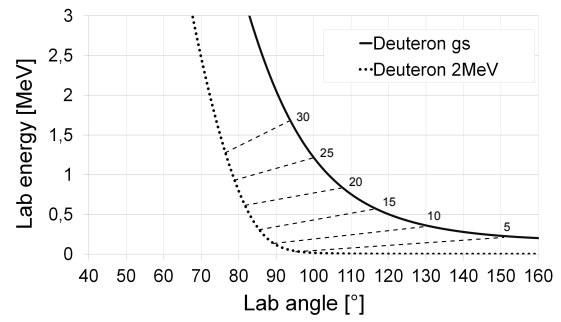


(b) Lab energy of ^2H (dashed line) and ^{67}Ni (solid line) versus CM angle ϑ_R of the recoiling nucleus ^2H in the (t, d) transfer reaction to the ground states of ^{67}Ni .

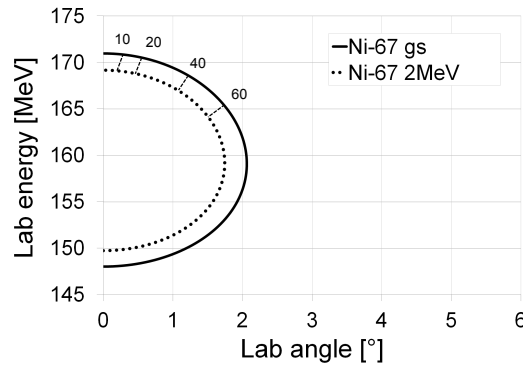
Figure 3.5: Kinematics of the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ to the ground state of ^{67}Ni .



(a) Deuteron lab energy versus lab angle.



(b) Deuteron lab energy versus lab angle.



(c) ^{67}Ni lab energy versus lab angle.

Figure 3.6: Plectrum plot of the (t, d) reaction to the ground state of ^{67}Ni (solid line) and to a fictitious excited state at 2 MeV (dotted line). Lab energy versus lab angle. The dashed lines show the corresponding CM angle.

surface of the nucleus.

In inverse kinematics low CM angles of ^2H correspond to large lab angles. In figure 3.6b one can see that for these angles the kinematic lines of the (t, d) reaction to the

ground state and to the 2 MeV state are compressed. The energy of the deuteron is small and does not vary much with the Q -value. This kinematic compression is a major issue of experiments in inverse kinematics when only the light recoiling particle is detected [Win97]. It imposes higher requirements on the energy resolution of the detection system. Furthermore one can see that deuterons from a transfer reaction to a 2 MeV state emitted at lab angles over 100° do not have sufficient kinetic energy to reach the detector. Moreover also deuterons from a transfer reaction populating the ground state emitted at high lab angles have low energy and will not be able to penetrate through the ΔE detector, as will be shown in section 4.1.1 in chapter 4. Consequently the identification of these particles in the data analysis will be cumbersome.

3.2 Scattering Theory

An important quantity in reaction theory is the *cross section* σ , the cross section of an $A(a, b)B$ reaction is defined as [Sat90]:

$$\sigma = \frac{\text{number of particles } b \text{ emitted}}{(\text{number of incident particles } a) \times (\text{number of target nuclei within the beam})}. \quad (3.4)$$

The cross section is a measure of the relative probability for a reaction to occur. In nuclear physics, cross sections are most often expressed in *barn* (symbol b , $1 b = 100 \text{ fm}^2$), which has the dimensions of area. The term *total* cross section is reserved to the sum of the cross section of all possible outcomes in the reaction of particles a and A .

Another important quantity is the *differential cross section* $d\sigma/d\Omega$ and corresponds to the number of particles b emitted per unit time within an element of solid angle $d\Omega$ in the direction with polar angles (θ, ϕ) with respect to the incident beam. The unit of the differential cross section is barns per steradians. The differential cross section of a transfer reaction shows a diffraction pattern, this pattern is related to the angular momentum $\ell\hbar$ that is transferred in the reaction. From conservation of angular momentum it is possible to put constraints on the spin of the nuclear states of particles b and B . Furthermore also the parity of the nuclear state can be deduced. In a nuclear reaction the parity $\pi_a\pi_A(-1)^\ell$ is conserved. To illustrate the spectroscopic strength of this technique suppose the shape of the angular distribution of the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ reaction to the ground state corresponds to $\ell = 1$. The intrinsic spin of the transferred neutron is $1/2$, by coupling the intrinsic spin to the transferred angular momentum the total transferred angular momentum is $1/2$ or $3/2$. By coupling the total transferred momentum to the 0^+ ground state spin of ^{66}Ni , one finds that the ground state spin of ^{67}Ni is either $1/2$ or $3/2$. The parity of the initial state $\pi_t\pi_{^{66}\text{Ni}}(-1)^\ell$ is negative. Since the ground state of the deuterons is a positive parity 0^+ state, the ground state of ^{67}Ni is either a $1/2^-$ or $3/2^-$ state. Unfortunately from the angular distribution no distinction between parallel or anti-parallel spin-orbit couplings can be made. On the basis of a transfer reaction no fixed spin assignment can be made. It does narrow down the possible options. From other experimental data or theoretical considerations the spin and parity can be assigned, e.g. from the shell model the ground state is expected to have a $\nu 2p_{1/2}$ configuration. Taking this into account the ground state spin can be tentatively assigned to be a $1/2^-$ state.

In the following, the formalism of nuclear scattering theory will be presented.

The reaction is initiated by the collision of particles a and A , this partition or entrance channel will be denoted by α . The outgoing particles b and B will be referred to as the exit channel β . In quantum mechanics the initial state of the system α is described by a wave function Ψ_α ,

$$\Psi_\alpha = A_0 e^{i\mathbf{k}_\alpha \cdot \mathbf{r}_\alpha} \psi_a \psi_A, \quad (3.5)$$

where A_0 is a normalization constant, $\mathbf{k}_\alpha$ is the relative momentum and $\mathbf{r}_\alpha$ is the separation of a and A . The radial part of the initial wave function is a plane wave with coordinates $\mathbf{r}_\alpha$ and $\mathbf{k}_\alpha$. This wave function also includes the internal degrees of freedom of the particles a and A (such as the spin and its state of excitation) this is incorporated in the normalized wave functions ψ_a and ψ_A .

In the reaction outgoing particles are produced. The total wave function of the state of the total system after the collision is represented by Ψ , this wave function contains all information on the different reaction channels,

$$\Psi = A_0 e^{i\mathbf{k}_\alpha \cdot \mathbf{r}_\alpha} \psi_a \psi_A + \sum_{\beta} \Psi_{\text{scatt},\beta}, \quad (3.6)$$

The total wave function of the system after the interaction consists of the initial partition α and all possible outcomes $b + B$ denoted by β . The sum over β also contains the elastic scattering channel. At the interaction point (at the target nucleus) the form of the wave function is not known exactly. At large distances outside the range of the interaction potential⁵ the wave function of the scattered wave is known and has the form:

$$\Psi_{\text{scatt},\beta}^{\text{ext}} = A_0 f_\beta(\theta, \phi) \frac{e^{i\mathbf{k}_\beta \cdot \mathbf{r}_\beta}}{r_\beta} \psi_b \psi_B, \quad (3.7)$$

When the interaction potential is spherically symmetric then the outgoing waves are spherical waves and their intensity falls off as $1/r_\beta^2$. The factor $f_\beta(\theta, \phi)$ is called the *scattering amplitude* and is related to the probability of channel β to be produced in the collision of a and A , hence to the differential cross section of $A(a, b)B$:

$$\frac{d\sigma_\beta}{d\Omega} = \frac{v_\beta}{v_\alpha} |f_\beta(\theta, \phi)|^2, \quad (3.8)$$

where v_α and v_β are the relative velocities of the partitions. In the case of elastic scattering one has $v_\alpha = v_\beta$. Expression (3.8) is valid when the particles have no spin or when the initial spins are randomly oriented, if not it must be averaged over the initial spin orientations and summed over the final spin orientations. To find the scattering amplitude one must solve the Schrödinger equation. There are two boundary conditions to take into account, first of all the incoming wave is a plane wave, secondly the scattered wave function has the form of equation (3.7) at large distances from the scattering center. The Schrödinger equation is

$$\left[\frac{-\hbar^2}{2\mu_\alpha} \nabla_\alpha^2 + H_a + H_A + V_\alpha \right] \Psi = E\Psi \quad (3.9)$$

⁵In the presence of a Coulomb potential with an infinite range this wave function is not correct. The wave function will be distorted but still obeys the inverse square law.

where μ_α is the reduced mass and E is the energy of the system. The first term represents the kinetic energy of the relative motion of the particles a and A , H_a and H_A are the Hamiltonians of the internal degrees of freedom of the particles such that $H_a\psi_a = \epsilon_a\psi_a$ and $H_A\psi_A = \epsilon_A\psi_A$. The potential V_α governs the interaction of the particles and produces the outgoing channel β . When the wave function Ψ is written as a sum of all possible internal states of a and A ,

$$\Psi = \sum_{a'A'} \chi_{a'A'}(\mathbf{r}_\alpha) \psi_{a'} \psi_{A'}, \quad (3.10)$$

then multiplied from the left by $\psi_a^* \psi_A^*$ and integrated over all internal coordinates,⁶ one obtains the following equation when inserted in the Schrödinger equation

$$\left[\frac{-\hbar^2}{2\mu_\alpha} \nabla_\alpha^2 + \epsilon_a + \epsilon_A + \langle aA | V_\alpha | aA \rangle - E \right] \chi_{aA}(\mathbf{r}_\alpha) = \sum_{a'A' \neq aA} \langle aA | V_\alpha | a'A' \rangle \chi_{a'A'}(\mathbf{r}_\alpha). \quad (3.11)$$

This equation shows that the wave function of the system $a + A$ is related to all possible outcomes $a'A'$ which can be the elastic channel or inelastic channels. When a large number of terms, involving high excited states are included in the expansion of Ψ , then even rearrangement collisions with outgoing particles b and B can be described. The matrix elements $\langle aA | V_\alpha | a'A' \rangle$ of the interaction potential V_α represent the coupling of the initial state aA to the final state $a'A'$. The diagonal elements of this matrix are written on the left side of equation 3.11, they represent the coupling of channel aA to aA , thus elastic scattering. The non-diagonal elements are on the right side of the equation and correspond to non-elastic channels. This equation allows thus to describe inelastic scattering or even rearrangement collisions. It shows that all reaction channels are coupled to one-another, for instance how the elastic channel is affected by the other reaction channels. This equation can also be constructed starting from any other couple $a'A'$ instead of aA . Ofcourse the correct boundary conditions must be taken into account, namely at large distance from the interaction point the wave function has the form of equations (3.6) and (3.7). Since equation (3.10) can be projected onto any state, an infinite set of these equations which are called *coupled equations* can be constructed. When all matrix elements $\langle aA | V_\alpha | a'A' \rangle$ are known the scattering amplitude for any reaction can be calculated. There is however an infinite number of matrix elements which makes these equations unpractical to perform calculations. In practice approximations have to be made.

Partial Wave Expansion

In scattering from a central potential one can expand the angular dependence of the wave function describing the relative motion of the scattering in terms of the orthonormal functions Y_l^m . The functions Y_l^m are the spherical harmonics with eigenvalues $l(l+1)$ for the orbital angular momentum operator squared $\mathbf{L}^2$ and m for $\mathbf{L}_z$. This property is very useful in the description of a reaction since often only a few terms of the expansion have to be considered. Classically the maximum orbital angular momentum transfer l depends on the range of the interaction R . Only when the impact parameter b is smaller than

⁶The orthogonality property of the internal wave functions is used, $\int \psi(\tau_a)^* \psi(\tau_{a'}) d\tau_{a'} = \delta_{aa'}$.

R , particles will interact. Since the angular momentum transfer is related to the impact parameter and the momentum $\hbar k$, via $l\hbar = \hbar k b$, only l values for which $l \leq kR$ have to be considered in the expansion. For simplicity, consider that the particles have no spin or other internal degrees of freedom and the interaction is spin-independent, as a result the wave function ψ is independent of the azimuthal angle ϕ . The wave function can be written as

$$\psi(\mathbf{r}, \theta) = \sum_{lm} c_{lm} \frac{\chi_l(r)}{r} Y_l^m(\theta, \phi) \quad (3.12)$$

where c_{lm} are normalization constants and $\chi_l(r)/r$ represents the radial dependence of the wave function in the expansion. This expansion is called the *partial wave expansion*. This expansion is allowed when the potential $V(r)$ is spherically symmetric. To be physically acceptable the $\chi_l(r)$ must satisfy the radial equation

$$\left[\frac{-\hbar^2}{2\mu} \left(\frac{d^2}{dr^2} - \frac{l(l+1)}{r^2} \right) + V(r) - E \right] \chi_l(r) = 0. \quad (3.13)$$

Outside the interaction potential we know the radial part of the wave function has the form $f_\beta \exp(i\mathbf{k}_\beta \cdot \mathbf{r}_\beta)/r_\beta$. Using this boundary condition, the scattering amplitude can be expressed as a sum over the angular momenta l .

$$f_\beta(\theta) = \frac{1}{2ik_\alpha} \left(\frac{\nu_\alpha}{\nu_\beta} \right)^{1/2} \sum_l (2l+1) [\eta_{l,\beta} - \delta_{\alpha\beta}] P_l(\cos\theta) \quad (3.14)$$

This equation is only valid when the particles have no spin and when the interaction is spin independent⁷. The factor $\eta_{l,\beta}$ is called the *partial wave scattering amplitude* or *scattering matrix element* and $\delta_{\alpha\beta}$ is the Kronecker delta ($\delta_{\alpha\beta} = 1$ when $\alpha = \beta$ and 0 otherwise). $\eta_{l,\beta}$ is an element of the unitary matrix η_l and represents the amplitude of the transition from entrance channel α to the exit channel β transferring l units of angular momentum. The partial wave scattering amplitudes are related to the matrix elements $\langle aA | V_\alpha | a'A' \rangle$ in equation (3.11). The unitarity of this matrix η_l ensures the conservation of flux. This way the reaction channels are coupled to one-another. When all matrix elements of $\eta_{l,\beta}$ of each l are known the differential cross section can be calculated. The matrix elements must be obtained by solving the Schrödinger equation in (3.13) with the proper boundary conditions. The advantage of this approach is that the three dimensional Schrödinger equation is reduced to a one dimensional radial equation for a series of l -values.

Coulomb Effects

The form of the outgoing scattered wave in equation (3.7) is correct when the wave is outside the range of the interaction. This equation is correct if only the short ranged nuclear interaction is present, however for charged particles the *Coulomb interaction* plays an important role. The Coulomb interaction is a long range interaction, the potential has a $1/r$ dependence. The Coulomb interaction will distort the outgoing wave even at large distances. Taking this into account it can be found that the wave function will have the following form at large distances

⁷We have made use of the fact that only the $m = 0$ component contributes and $Y_l^0 = [(2l+1)/4\pi]^{1/2} P_l(\cos\theta)$

$$\frac{1}{\mathbf{r}} \exp(i\mathbf{k}_\beta \cdot \mathbf{r} - n_\beta \ln 2\mathbf{k}_\beta \cdot \mathbf{r}), \quad (3.15)$$

where n_β is the *Sommerfeld* parameter $n_\beta = Z_b Z_\beta e^2 / \hbar v_\beta$. Consequently the differential cross section will be affected by this Coulomb distortion. The differential cross section is then given by

$$\frac{d\sigma_\beta}{d\Omega} = \frac{v_\beta}{v_\alpha} |f_C(\theta)\delta_{\alpha,\beta} + f'_\beta(\theta, \phi)|^2, \quad (3.16)$$

where $f_C(\theta)$ is the Rutherford scattering amplitude which contributes to the elastic channel and $f'_\beta(\theta, \phi)$ is the Coulomb distorted scattering amplitude.

In the following we will not specifically note the effect of the Coulomb potential. To do this the following transformations should be performed:

$$\begin{aligned} \mathbf{k}_\beta \cdot \mathbf{r}_\beta &\rightarrow [\mathbf{k}_\beta \cdot \mathbf{r}_\beta + n_\beta \ln (k_\beta r_\beta - \mathbf{k}_\beta \cdot \mathbf{r}_\beta)] \\ k_\beta r_\beta &\rightarrow (k_\beta r_\beta - n_\beta \ln 2k_\beta r_\beta) \end{aligned}$$

3.3 The Optical Model

Until now we have discussed the general description of nuclear scattering. To solve the Schrödinger equation in (3.9) or (3.13) the interaction potential V must be known. However this interaction potential is a complicated many-body problem. In the *optical model* the potential is described by a smoothed average of the actual interaction. This approach has been very successful in the description of elastic scattering. To describe elastic scattering one must take into account that the interaction may also result in non-elastic scattering. The existence of these reaction channels affects the elastic channel, thus they have to be taken into account. The optical model deals with this using imaginary components in the potential. This way the interaction has an absorptive character, removing an amount of flux from the elastic channel and adding this to the non-elastic channels. Scattering potentials with both an imaginary and real component are called optical potentials due to the resemblance with the description of the optical refractive index of light. The angular distribution of scattered particles shows a diffraction pattern similar to the diffraction pattern of light incident on a disc. The propagation of light through an opaque disc can be described by using a complex index of refraction. A similar description works for nuclear scattering with particles. A typical optical model potential consists of the following components:

$$V = -V_r f_r(r) - i4a_D W_D \frac{df_D(r)}{dr} + 2\lambda_\pi^2 \frac{V_{so}}{r} \frac{df_{so}(r)}{dr} \mathbf{1} \cdot \mathbf{S} + V_C(r), \quad (3.17)$$

The potential consists of four types of interactions.

- an attractive nuclear interaction term V_r ,
- an imaginary surface absorption term W_D ,
- a spin-orbit term V_{so} ,
- and a Coulomb potential V_C .

The interaction potentials have a Woods-Saxon form or the derivative of a Woods-Saxon potential in the case of surface interactions,

$$f_i(r) = (1 + \exp(\frac{r - R_i}{a_i}))^{-1}. \quad (3.18)$$

The interaction range R_i is calculated as $r_i(A_1^{1/3} + A_2^{1/3})$ where A_1 and A_2 are the mass numbers of the colliding particles and r_i is a parameter of the model and usually 1.2 to 1.4 fm. The parameter a_i represents the diffuseness of the potential. The coefficients V_r , W_D , V_{so} are the amplitudes of the interactions. The Coulomb potential $V_C(r)$ is taken as the potential of a uniformly charged sphere with radius R_C ,

$$V_C(r) = \begin{cases} \frac{Z_1 Z_2 e^2}{2R_C} (3 - \frac{r^2}{R_C^2}), & \text{for } r \leq R_C \\ \frac{Z_1 Z_2 e^2}{2R_C}, & \text{if } r > R_C. \end{cases} \quad (3.19)$$

Figure 3.7 shows the shape of the different components of the optical model.

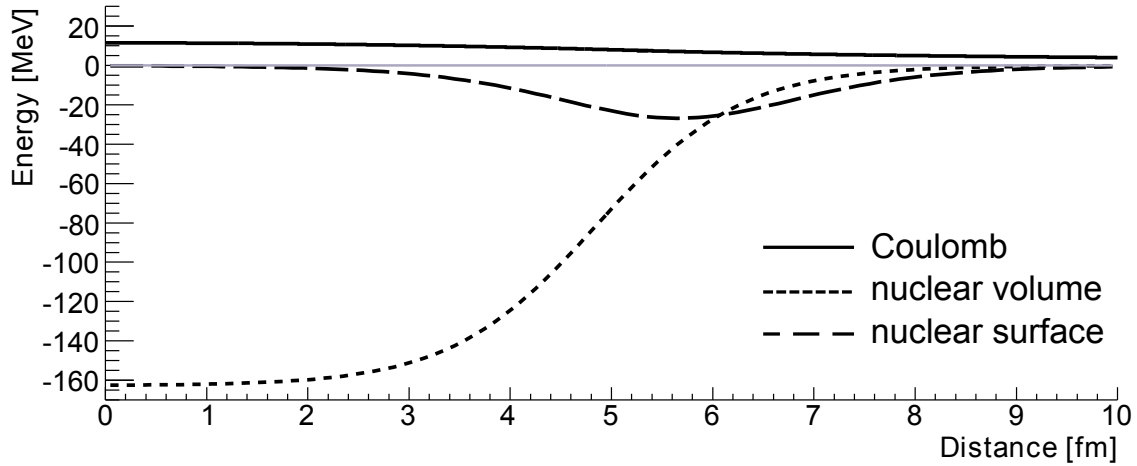


Figure 3.7: Components of the optical potential of the form 3.17 for elastic scattering of 7.8 MeV tritons on a ^{66}Ni target.

The absorptive part of the potential is taken as the derivative of the Woods-Saxon potential which peaks at the surface. This choice of potential shape is based on the fact that mostly the outer nucleons are involved in inelastic collisions. They are able to absorb energy, for the inner nucleons there is no possibility to absorb energy as all nearby energy levels are occupied. The spin orbit interaction is represented by a real term V_{so} with a $\frac{1}{r} \frac{df}{dr}$ shape, λ_π^2 is the Compton wavelength of the pion squared, $\lambda_{pi}^2 = 2.0 \text{ fm}^2$.

In total the model has 13 free parameters. The potential parameter can be obtained by fitting this functional to experimental data. Another option is to use global optical parameters (OMP's). Over the years many scattering experiments have been performed and many cross sections have been measured. Empirical relations of the OMP's as function of energy, mass and asymmetry ($N - Z$) of protons and neutrons have been developed. An attempt to develop a global model for the OMP parameters for elastic proton and neutron scattering was done by Becchetti and Greenlees [BG69] in 1969 for $A > 40$ and $E < 50$ MeV. Later, global optical model parameters for deuteron, alpha and triton scattering

were developed [PP76, Lea07]. In this thesis we will make use of global OMP's from Becchetti and Greenlees [BG69, PP76] for triton scattering and from Han et al. [Hea06] for the deuteron channel. The optical model for deuteron elastic scattering that is used in the DWBA calculations of the (t, d) reaction will be discussed next.

3.4 The DWBA Theory

In this section the distorted-wave Born approximation (DWBA) transfer theory will be introduced. For several decades the DWBA theory has been and still is the most used and successful theoretical framework to describe transfer reactions and inelastic scattering.

3.4.1 The Schrödinger Equation and Transition Amplitude

We start from the Schrödinger equation in (3.9) and for simplicity the internal degrees of freedom of particles a and A are not considered. Using $U = 2\mu V/\hbar^2$ and $k = [2\mu E/\hbar^2]^{1/2}$ where μ is the reduced mass, the equation can be rewritten as:

$$(\nabla^2 + k^2)\chi(\mathbf{r}) = U(\mathbf{r})\chi(\mathbf{r}) \quad (3.20)$$

The presence of the potential $U(r)$ creates scattered waves in addition to the incoming plane wave. One can calculate that for an incoming plane wave the solution of the Schrödinger equation outside the range of the potential is

$$\chi(\mathbf{k}, \mathbf{r})^{ext} = e^{i\mathbf{k}\cdot\mathbf{r}} - \frac{\exp(ik\mathbf{r})}{4\pi\mathbf{r}} \int \frac{\exp(ik|\mathbf{r} - \mathbf{r}'|)}{|\mathbf{r} - \mathbf{r}'|} U(\mathbf{r}')\chi(\mathbf{k}, \mathbf{r}')d\mathbf{r}'. \quad (3.21)$$

By comparison of this form to the external wave function in equations (3.7) and (3.8) an expression for the scattering amplitude f_β can be obtained. The resulting scattering amplitude is the coefficient of the outgoing scattered wave of the form $\exp(i\mathbf{k}\mathbf{r})/\mathbf{r}$.

$$f_\beta(\theta, \phi) = -\frac{1}{4\pi} \int \exp(-i\mathbf{k}' \cdot \mathbf{r}') U(\mathbf{r}')\chi(\mathbf{k}, \mathbf{r}')d\mathbf{r}' \quad (3.22)$$

Unfortunately $f_\beta(\theta, \phi)$ cannot be calculated exactly since the wave function $\chi(\mathbf{k}, \mathbf{r}')$ which is present in the integral is not known. This is however a useful starting point for approximations. One can use another (known) wave function as input in the integral and calculate the scattering amplitude. In the following two approximations will be discussed, the Plane-Wave Born Approximation (PWBA) and the Distorted-Wave Born Approximation.

In the discussion of these approximations, the internal degrees of freedom of the particles will be introduced again and the formalism of transition amplitudes $T_{\beta\alpha}$ will be used. The transition probability is frequently expressed by the transition amplitude $T_{\beta\alpha}$, this quantity is related to the scattering amplitude via $T_{\beta\alpha} = \frac{-2\pi\hbar^2}{\mu_\beta} f_\beta$, using equation (3.8) the differential cross section can then be expressed as:

$$\frac{d\sigma_\beta}{d\Omega} = \frac{\mu_\alpha\mu_\beta}{(2\pi\hbar^2)^2} \left(\frac{k_\beta}{k_\alpha}\right) |T_{\beta\alpha}|^2 \quad (3.23)$$

3.4.2 Plane-Wave Born Approximation

In the plane-wave Born approximation the wave function $\chi(\mathbf{k}, \mathbf{r}')$ of the final wave function is approximated by the solution of the Schrödinger equation for $U(r) = 0$, i.e. a plane wave. Doing so, and introducing the internal degrees of freedom, the transition amplitude is given by:

$$\begin{aligned} T_{PWBA} &= \int \int \exp(-i\mathbf{k}_\beta \cdot \mathbf{r}_\beta) \underbrace{\langle \psi_B \psi_b | V | \psi_a \psi_A \rangle}_{F(\mathbf{r}_\alpha, \mathbf{r}_\beta)} \exp(i\mathbf{k}_\alpha \cdot \mathbf{r}_\alpha) d\mathbf{r}_\alpha d\mathbf{r}_\beta \\ &\approx \int \exp(i\mathbf{q} \cdot \mathbf{r}) F(\mathbf{r}) d\mathbf{r}, \quad \mathbf{q} = \mathbf{k}_\alpha - \mathbf{k}_\beta, \end{aligned} \quad (3.24)$$

where $\mathbf{q}$ is the change in momentum of the scattered particles and $F(\mathbf{r}_\alpha, \mathbf{r}_\beta)$ is called the *nuclear matrix element*, this term contains important nuclear properties which we want to investigate. To obtain equation (3.24) we made the assumption: $\mathbf{r}_\alpha \approx \mathbf{r}_\beta \approx \mathbf{r}$. Physically this means that the particle b is emitted at the same point where a is absorbed. It significantly reduces the effort that has to be made in the calculations, though computer codes can already deal with the finite-ranged form.

The nuclear matrix element can be written as a multipole series

$$F(\mathbf{r}) = \sum_{lm} f_l(r) Y_l^m(\theta, \phi), \quad (3.25)$$

where $f_l(r)$ are called *form factors* representing the radial part of the expansion and Y_l^m are the spherical harmonics. Usually the nuclear spins and possibly structural selection rules allow only one or at least only a few values of angular momentum to be transferred. It is therefore useful to also write $\exp(i\mathbf{q} \cdot \mathbf{r})$ as a partial wave expansion,

$$\exp(i\mathbf{q} \cdot \mathbf{r}) = 4\pi \sum_l i^l j_l(qr) \left[\sum_m Y_l^m(\theta_r, \phi_r) Y_l^m(\theta_q, \phi_q)^* \right],$$

where the $j_l(qr)$ are the spherical Bessel functions. Now if only one l -value from this expansion is allowed then only the l th partial wave must be taken into account. Furthermore we assume that there is strong absorption in the nuclear interior ($r < R$) due to compound nuclear reactions. In other words, the wave functions are zero inside the nucleus. Then the integration is restricted to $r \geq R$. Moreover the form factor $f_l(r)$ is a nuclear property and rapidly falls off beyond the nuclear surface. As a result the integral can be approximated by evaluating equation (3.24) at the nuclear surface R . In this case the differential cross section is proportional to the l th spherical Bessel function squared:

$$\frac{d\sigma_\beta}{d\Omega} \sim [j_l(qR)]^2$$

The angular dependence of the differential cross section becomes clear from the fact that

$$q = [k_\alpha^2 + k_\beta^2 - 2k_\alpha k_\beta \cos \vartheta]^{1/2},$$

where ϑ is the angle of emission of b relative to the incident beam in the CM frame. This gives more insight in the experimentally observed oscillatory behaviour of the differential cross section in scattering experiments. The mode of oscillation is directly related to the

transferred angular momentum. However the way the nuclear interior has been excluded by assuming strong absorption is rather crude. Physically one cannot have a wave function with a hole in the nuclear interior and an undistorted plane wave at large distances. The DWBA approach deals with this matter in another way.

3.4.3 Distorted-Wave Born Approximation

In the DWBA theory the relative motions before and after the collision are not described by plane waves but by distorted waves χ_α and χ_β (representing the entrance and exit channel respectively). These wave functions are solutions of elastic scattering of particles $a + A$ and $b + B$ using optical potentials U_α and U_β , respectively⁸. At large distances they have the asymptotic form as in equations (3.6) and (3.7). The optical potentials induce elastic scattering, and provide an amount of flux to the non-elastic channels through the imaginary components. The non-elastic scattering itself is governed by another potential V . This potential induces the transition from α to β . Approximating the motion of the particles before and after the collision as distorted waves is valid when non-elastic scattering is less likely to occur than elastic scattering. This usually is the case. The non-elastic events can then be treated as perturbations. The DWBA transition amplitude is:

$$T_{DWBA} = \int \int \chi_\beta^{(-)}(\mathbf{k}_\beta, \mathbf{r}_\beta)^* \langle \psi_B \psi_b | V | \psi_A \psi_a \rangle \chi_\alpha^{(+)}(\mathbf{k}_\alpha, \mathbf{r}_\alpha) d\mathbf{r}_\beta d\mathbf{r}_\alpha, \quad (3.26)$$

$\chi_\beta^{(-)}(\mathbf{k}_\beta, \mathbf{r}_\beta)$ is the distorted wave of the exit channel consisting of a plane wave and an outgoing spherical wave, $\chi_\alpha^{(+)}(\mathbf{k}_\alpha, \mathbf{r}_\alpha)$ is composed of an incoming plane wave and an ingoing scattered spherical wave.

In this case it is not easy to obtain a simple analytic expression for the transition amplitude as in the PWBA theory. The physics however is not different from the previous procedure. Again the distorted waves are expanded in partial waves, and also the matrix element $\langle \psi_B \psi_b | V | \psi_A \psi_a \rangle$ is written as a multipole expansion as in equation (3.25) using the zero-range form (which means putting $\mathbf{r}_\alpha \approx \mathbf{r}_\beta \approx \mathbf{r}$). The six dimensional integral then reduces to a sum of one dimensional radial integrals. The integrals can be evaluated over the nuclear interior and outside the range of the interaction.

To evaluate the matrix element $\langle \psi_B \psi_b | V | \psi_A \psi_a \rangle$, the internal wave functions have to be described in a certain model. In stripping or pick-up reactions the wave functions are of the shell model type. For instance consider the transfer reaction:

$$a + A \rightarrow b + B; \quad a = b + x, \quad B = A + x.$$

where a single nucleon x is transferred to the target nucleus A . In the calculations one particular pure shell model configuration is considered. The internal wave functions are factorized and normalized. The internal wave function of B can be written as:

$$\psi_B = (\psi_A \phi_x)_J,$$

where ψ_A is the internal wave function of A and ψ_x is the shell model orbital in B in which nucleon x is placed. The final nucleus B is thus described as the initial nucleus A

⁸In the PWBA approach the wave functions were solutions of scattering on a $U = 0$ potential.

plus a nucleon in a particular shell model orbital. The spin of A and ψ_x are coupled to J , the spin of the populated state of B .

The interaction potential V is a function of the position of the transferred nucleon $\mathbf{r}_x$ and the emitted particle $\mathbf{r}_b$. Because of the short-ranged character of the nuclear interaction the potential can be approximated by $V(\mathbf{r}_b - \mathbf{r}_x) \approx D_0 \delta(\mathbf{r}_b - \mathbf{r}_x)$, where $\delta(\mathbf{r}_b - \mathbf{r}_x)$ is the Kronecker delta function. This approximation is called the *zero-range approximation*.

In this reaction the nucleon is placed in a specific shell model orbital of B . Hence in the multipole expansion of the nuclear matrix element only one l -value has to be considered, i.e. the orbital angular momentum transfer allowed by the spin and parity of the shell model orbital in which the nucleon is placed. After the partial wave expansion of the distorted waves and this nuclear matrix element the transition amplitude is reduced to a one dimensional radial integral over the allowed l -component of the expansion. As a result, the differential cross section will show a specific angular dependence related to the transferred l -value.

As mentioned before, the calculations assume pure shell model configurations. However actual nuclear states that are populated can have a mixed configuration. By comparison of the calculated and experimental differential cross sections *spectroscopic factors* SF can be obtained.

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = SF \left(\frac{d\sigma}{d\Omega}\right)_{DWBA} \quad (3.27)$$

The spectroscopic factor is a measure of how well the populated state in B resembles the initial nucleus A plus a nucleon in a particular shell model orbital. A spectroscopic factor of 1 means the populated state perfectly corresponds to a pure single-particle state as in the extreme independent particle model. When the spectroscopic factor is lower than one, then the populated nuclear state is a mixing of different configurations. Or also, the strength of this shell model orbital resides in multiple excited states. In this perspective transfer reactions are a powerful tool to investigate the shell model and nuclear structure. Single nucleon transfer reactions are excellent probes for the single-particle character of nuclear states.

Let us consider the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ transfer reaction to the ground states of ^{67}Ni and ^2H . Initially the transferred neutron is in a $\nu s_{1/2}$ shell model orbital in the triton and ^{66}Ni has a 0^+ ground state. In the final state the deuteron has a 1^+ ground state and we assume the ground state of ^{67}Ni has a $\nu p_{1/2}$ configuration. The neutron is transferred from a $s_{1/2}$ ($l = 0$) to a $p_{1/2}$ ($l = 1$) orbital, hence from parity considerations only odd l -values are possible. In fact only $l = 1$ is possible since a spin $1/2$ neutron cannot couple to a $1/2$ state with $l = 3$ or any higher l -value. This procedure can be done for any populated state of ^{67}Ni , every time one has to assume a certain shell model configuration. The probability of this transition depends on how strongly the wave function of this state overlaps with the ground state of ^{66}Ni . One can determine to what degree the populated eigenstate in ^{67}Ni looks like ^{66}Ni with one additional neutron in a particular shell model orbit. This can give us valuable information on how to interpret the observed excited states in the framework of the shell model. As discussed in chapter 1 the single-particle structure of ^{67}Ni is a probe of the magicity of ^{68}Ni .

Chapter 4

Data Analysis

To extract information on the internal structure of ^{67}Ni from the signals from Miniball, T-REX and the beamdump detectors it is necessary to select the desired events, namely the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ transfer reaction. By imposing specific conditions on timing, energy and position one can obtain clean data of different reaction channels. In this chapter the data analysis procedure will be discussed.

4.1 Kinematics of the Reaction Products

A first fingerprint of the different reaction channels is the kinematics of the reaction products. The kinematics offers constraints on the energy and trajectory of the emitted particles. As was shown in chapter 2 the detection system is designed to detect particles over a wide range of angles. Since the beam is not polarized the scattering amplitude is independent of the azimuthal angle ϕ and only the θ -dependence is of importance. In the forward and backward barrel detectors 16 strips cover the lab angles $\theta = 26^\circ$ to $\theta = 76.5^\circ$ and $\theta = 100^\circ$ to $\theta = 157^\circ$. By looking at the number of particles versus energy and position one can already identify some reaction channels. The particles that are detected in the forward and backward barrel and in the backward CD detector are shown in figure 4.1.

The figure shows the total number of detected particles as a function of lab energy and lab angle θ . In total $1.4 \cdot 10^7$ counts were registered in the particle detectors during the experiment. In the analysis of the data the forward CD detector was not used for several reasons. First of all, for the (t, d) reaction small deuteron lab angles correspond to large CM angles, in this region the variation in the differential cross section is very small and it is hard to discriminate transfer reactions with different angular momentum transfer $\ell\hbar$. Moreover due to the $50 \mu\text{m}$ Kevlar foil in front of the detector, the energy calibration is very elaborate and a good resolution cannot be obtained. For this reason the data from the forward CD detector has not been used in the analysis of the (t, d) reaction.

In fact the data analysis of the (t, d) reaction is limited to the forward barrel detector only. From the kinematics discussed in chapter 3 it can be seen that the energy of the deuterons emitted in backward direction ($\theta_{lab} > 90^\circ$) is lower than 2 MeV (see figures 3.6a and 4.3a). This is lower than the energy threshold of the backward detector. This threshold is set to reduce background but to still detect protons from the (t, p) transfer reaction (which was of main interest in the experiment performed in 2011). Hence the deuterons in backward

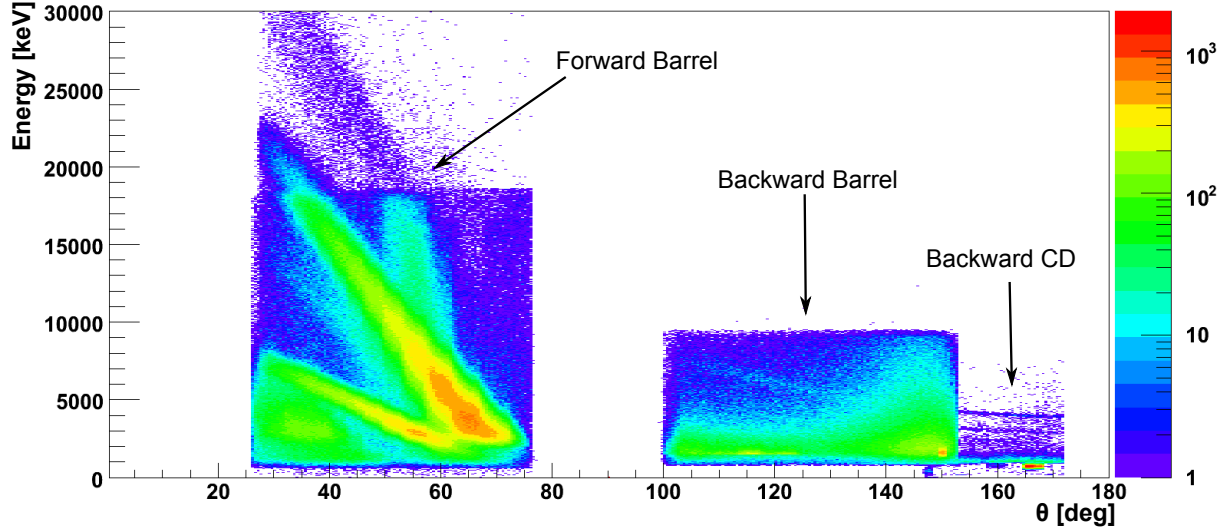


Figure 4.1: The total number of particles detected by the forward and backward barrel detectors and the backward CD detector versus energy and lab angle.

direction are lost. Therefore, in the following, only particles detected in the forward barrel are considered.

In figure 4.2 simulated kinematic curves of the different detected particles are shown. Tritons (solid blue curve) and ^3He (solid pink curve) can only originate from elastic scattering events, as they are present in the target¹. Protons can originate from two-neutron transfer from ^3H to ^{66}Ni (dashed black curves) as well as from elastic scattering (solid black curve). Deuterons can only be produced in the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ one-neutron transfer reaction (dashed red curves). The kinematic line of elastically scattered deuterons is drawn for completion. Alpha particles also occur and originate from a proton transfer reaction, $^{66}\text{Ni}(t, \alpha)^{65}\text{Co}$ (dashed yellow curve). The solid gray curve represents elastic scattered oxygen, this contaminant originates from the oxidation of the target.

The upper dashed red line is a simulation of the energy of a deuteron, emitted in a transfer reaction leaving ^{67}Ni in the ground state. This curve represents the same deuteron curve as in the plectrum plot in figure 3.6. Differences are due to the fact that the simulation takes into account all features of the detection setup, such as the dimensions of the telescope detectors, the target thickness and the foils. The lower dashed red line is a simulation of the energy of a deuteron emitted in a transfer reaction leaving ^{67}Ni in a fictitious excited state at 2 MeV. Consequently the measured energy of the deuteron is lower than for a transfer reaction to the ground state. The deuterons of interest lie in the region marked by the simulated curves. However in this region also other particles are detected. To perform an analysis of the $^{67}\text{Ni}(t, d)^{67}\text{Ni}$ reaction, it is necessary to select the deuterons from the data.

In the forward direction there is a pile-up of particles for lab angles $\theta < 50^\circ$ with an energy up to 5 MeV. This origin of this noise is difficult to determine since all particles are stopped in the ΔE detector. One possibility is that the noise stems from elastic scattering of ^{66}Ni on titanium in the target. For $\theta < 50^\circ$ the titanium nuclei and ^{66}Ni have sufficient amount of energy to penetrate through the Mylar foil and stop in the

¹The ^3He nucleus is the daughter of ^3H nucleus which undergoes β^- decay.

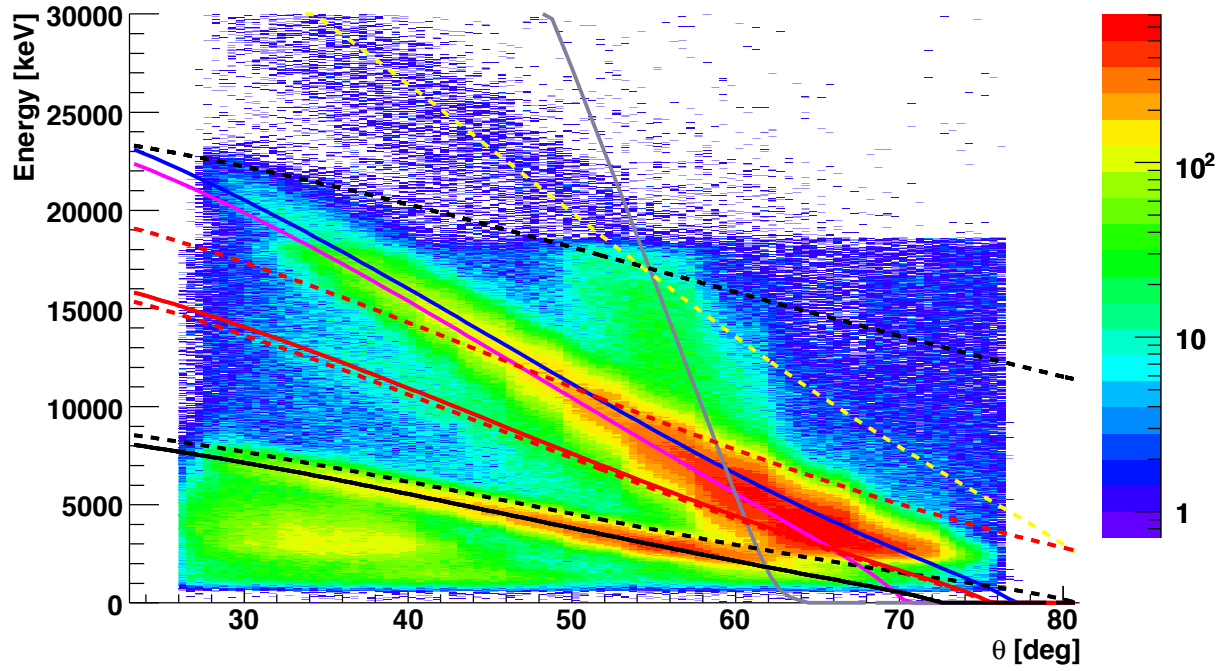
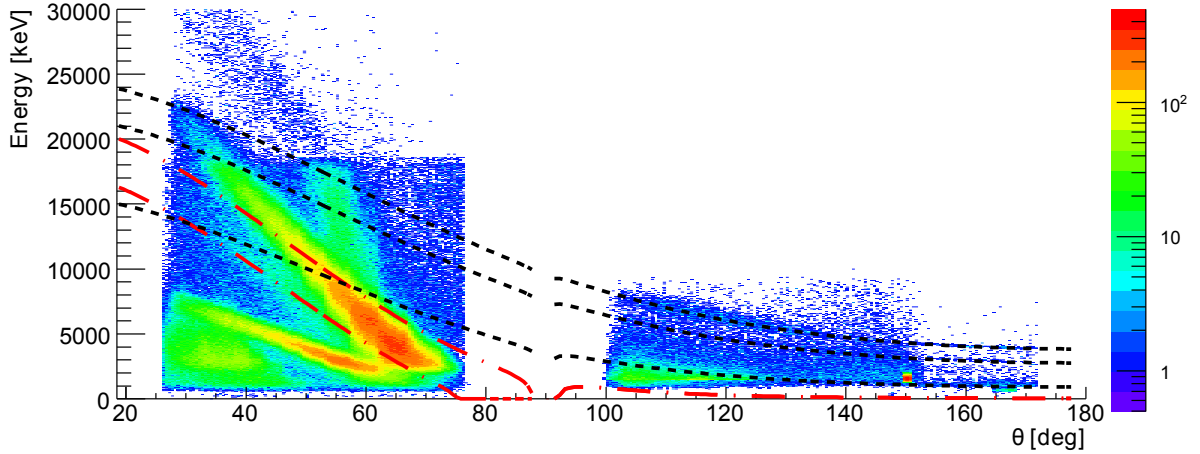


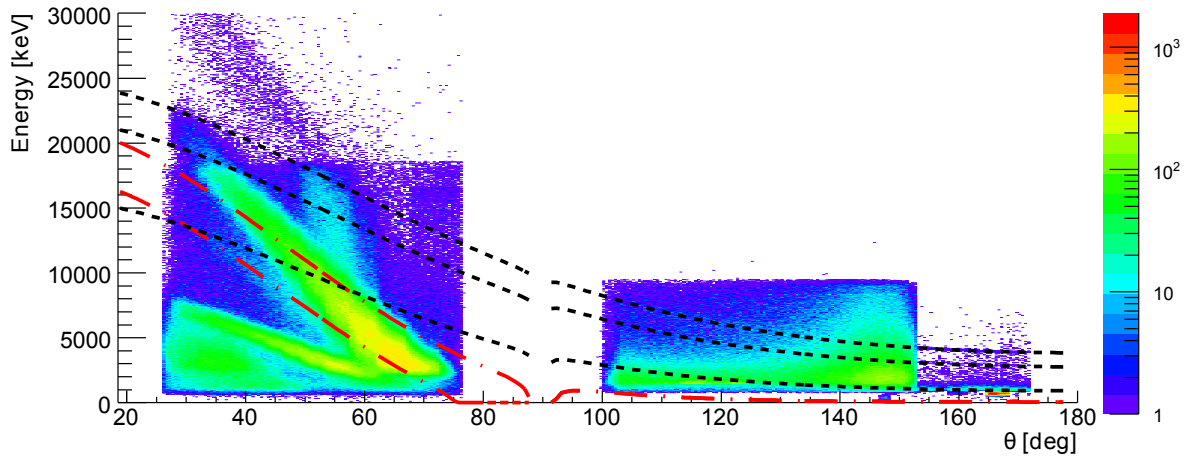
Figure 4.2: The total number of detected particles in the forward barrel detector versus energy and lab angle. Solid lines represent simulations of the kinematics of elastically scattered particles. The tritons in blue, deuterons in red, ^3He in pink, oxygen in grey and protons in black. The dashed lines represent simulations of the kinematics of particles originating from transfer reactions. The upper and lower dashed black lines show the kinematics of protons originating from a transfer reaction leaving ^{68}Ni in the ground state and in a fictitious excited state at 9.5 MeV, respectively. The upper and lower dashed red curves represent deuterons from a transfer reaction leaving ^{67}Ni in the ground state and in a fictitious 2 MeV excited state, respectively. The dashed yellow curve represents alpha particles from a $^{66}\text{Ni}(t, \alpha)^{65}\text{Co}$ pick-up reaction, leaving ^{65}Co in its ground state.

detector volume.

Also in the backward barrel and CD detector there is noise from $\theta = 100^\circ$ to $\theta = 125^\circ$ with an energy lower than 5 MeV. From $\theta = 125^\circ$ to $\theta = 154^\circ$ there is a lot of noise with energies up to 9 MeV. This noise is due to an incorrect beam tuning during the experiment. During the experiment the beam tuning was adjusted, it did however not lead to better experimental conditions. For 56,5% of the total run time the beam tuning was not optimal and the beam was partially stopped in the back of the target chamber. The situation before and after the beam tuning is shown in figure 4.3.



(a) Before beam tuning.



(b) After beam tuning.

Figure 4.3: Number of particles versus energy and lab angle in the Si detectors, the upper dashed black line represents the protons emitted in a transfer reaction to the ground state of ^{68}Ni , the lower dashed black lines show the protons emitted in a transfer reaction to a fictitious 2 MeV and 6 MeV excited state in ^{68}Ni . The upper dashed red line shows the kinematic lines of deuterons from the (t, d) transfer reaction to the ground state of ^{67}Ni , the bottom line to a fictitious state at 2 MeV. The top figure shows the situation with good beam tuning, the bottom figure shows the situation with the adjusted beam tuning.

Before the beam tuning there is only noise at low energies from $\theta = 100^\circ$ to $\theta = 125^\circ$

and at $\theta = 150^\circ$ around 2 MeV. At higher energy the protons from transfer reactions to the ground state of ^{68}Ni and to the 2033 keV excited state are clearly present. After the beam tuning the backward barrel detector is overloaded with noise. Fortunately in forward direction the signal is unaffected by the different beam tuning. This is an indication that part of the beam is stopped in the back of the target chamber. Further evidence of this is given by the γ spectrum before and after the beamtuning. After the beamtuning the γ spectrum measured by the Miniball detectors in backward direction suffers from a larger background from the β decay of ^{66}Cu than before the beamtuning, while the γ spectrum measured in forward direction is less affected.

4.1.1 Particle Identification

The T-REX silicon array is equipped with telescope ΔE - E detectors designed to identify the light recoiling particles from transfer reactions in inverse kinematics. The identification is based on the charge and mass dependence of the electric stopping power. The electronic stopping power $S = -\frac{dE}{dx}$ can be approximated by the Bethe-Bloch formula [FM86]:

$$-\frac{dE}{dx} = \frac{2\pi Z^2 e^4 n}{m_e v^2} \ln \frac{2m_e v^2}{I}, \quad (4.1)$$

where Z is the atomic number of the incoming particle, n is the electron density of the target, m_e is the electron mass, v is the velocity of the incoming particle and I is the average ionization energy of an electron. By integrating equation 4.1 over the path of the incoming particle in the ΔE detector the total energy deposited in the ΔE detector can be calculated. With SRIM [Zie08] simulation software the energy loss and range can be simulated taking into account electronic and nuclear stopping power of the target and incoming particle. These simulations give a better approximation of the energy loss and range of the particles than the Bethe-Bloch formula and will be used to identify the charged particles in so called ΔE - E plots. The telescope detectors measure the energy deposited in the ΔE detector and the energy deposited in the pad detectors. The energy deposited in the ΔE detector depends on the type of particle. By plotting ΔE versus the total energy E_{tot} , which is the sum of the energy deposited in the ΔE detector and in the pad detector, as in figure 4.4 the different particles can be identified.

Evidently tritons lose more energy in the ΔE detector than deuterons, and deuterons more than protons. For each strip of each quadrant of the forward and backward barrel detectors these ΔE - E plots are constructed. Each strip corresponds to a lab angle interval. With SRIM the energy loss in the ΔE detector is calculated for each strip, taking into account the kinematics of the reaction products and the path through the foils and the ΔE detector which varies as $L/\sin(\theta_{lab})$, where L is the thickness of the foil or the ΔE detector. Besides protons, deuterons and tritons also ^{66}Ni and titanium nuclei impinge on the ΔE detector in elastic scattering. However at lab angles close to 90° these particles are stopped in the Mylar foil, for low lab angles they can pass through the Mylar foil and are stopped in the ΔE detector. They can clearly be discriminated from the protons, deuterons and tritons.

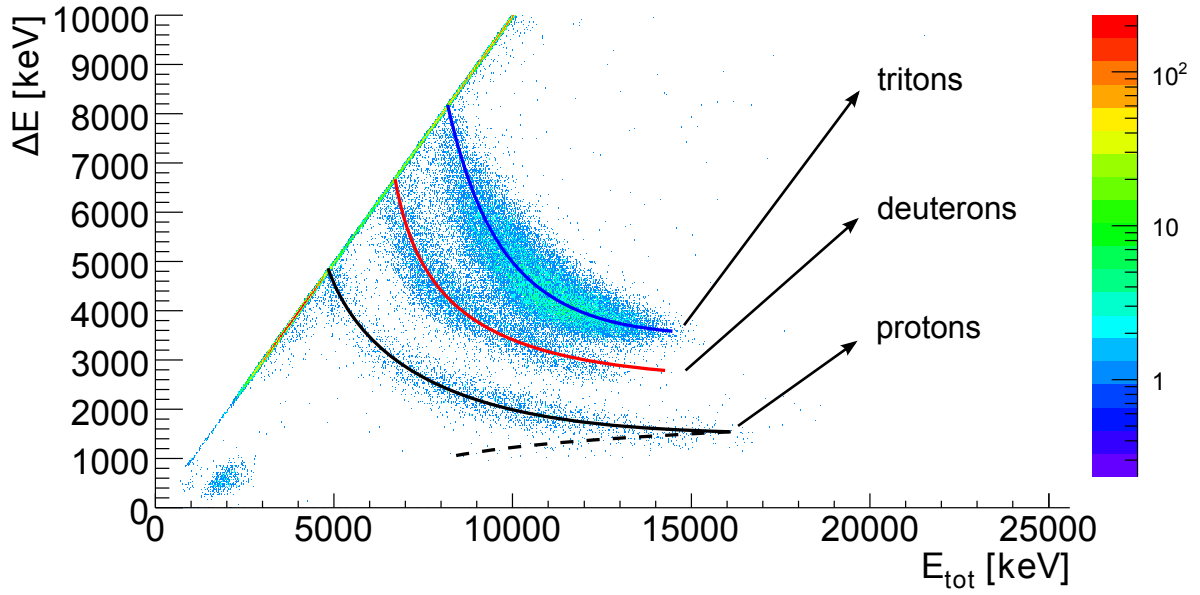


Figure 4.4: The energy deposited in the ΔE detector versus the total energy for strip 5 in the bottom quadrant of the forward barrel detector. This type of plot allows to identify protons, deuterons and tritons. The solid lines are calculated energy losses.

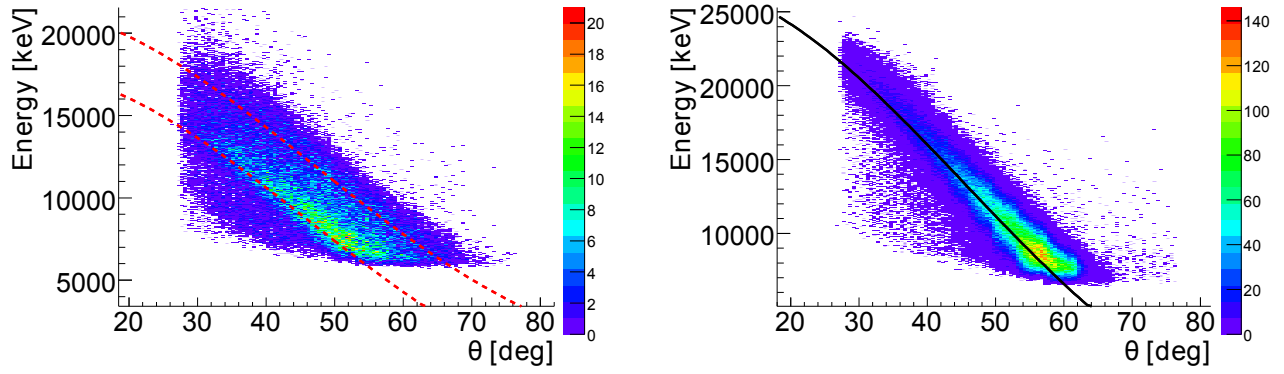
In the particle identification process via the ΔE - E plots three situations are considered.

(1) First of all the situation where particles pass through the ΔE detector and are stopped in the pad detector. In the ΔE - E plots these events form a banana shape. Since the stopping power scales with $\ln(v^2)/v^2$ as shown in equation 4.1, higher energetic particles lose less energy in the ΔE detector than low energetic particles. In this region one can accurately select the different light particles by means of a graphical cut.

(2) The second group of particles to consider are the particles that are stopped in the ΔE detector. In this case the particles can not be identified since their energy is fully deposited in the ΔE detector. Only lower and upper limits on the energy are defined for each type of particle in each strip of the detector.

(3) A third important case is when particles pass through both the ΔE detector and the pad detector. In this experiment this only occurs for high energetic protons. In these events the total energy deposited is less than the actual energy of the proton and the energy loss in the ΔE detector will be small. The dashed line in figure 4.4 shows the region of protons that pass through the telescope detector.

In the analysis of the (t, d) and (t, t) reaction we will only consider deuterons and tritons that pass through the ΔE detector and are stopped in the pad detector. The energy and lab angle of these deuterons and tritons are shown in figures 4.5a and 4.5b respectively.



(a) Energy of deuterons that pass through the ΔE detector versus lab angle. The upper and lower dashed red lines represent a (t, d) reaction to the ground state and to a fictitious 2 MeV state of ^{67}Ni .

(b) Energy of tritons that pass through the ΔE detector versus lab angle. The black curve represents the calculated kinematic line of elastic scattering of ^{66}Ni on ^3H .

Figure 4.5: Kinematics of identified deuterons and tritons that pass through the ΔE detector and are stopped in the pad detector.

4.2 d - γ Events

In this study only the γ rays from the decay of ^{67}Ni are of importance. ^{67}Ni can only be produced in a (t, d) transfer reaction and can decay by γ emission when left in an excited state. The (t, d) reaction is characterized by the emission of a deuteron which have been identified in the ΔE - E plots. It is now possible to select the γ rays from the (t, d) reaction by imposing a coincidence condition on the γ rays and deuterons. The time difference between the detection of a deuteron and the detection of a γ ray is shown in figure 4.6

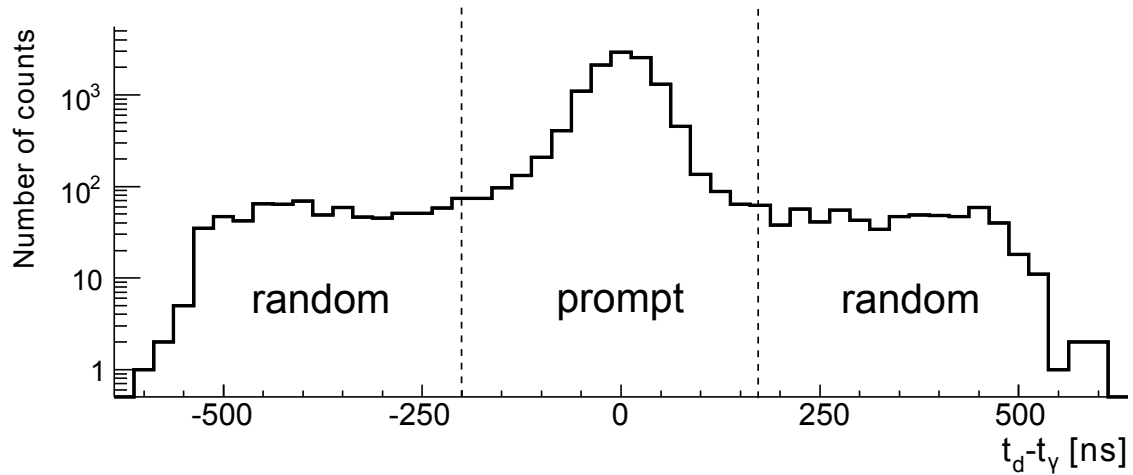


Figure 4.6: Time difference between deuterons detected by T-REX particle detector array and Miniball γ ray detector array. The dashed lines show the prompt coincidence interval.

Gamma rays are emitted shortly after the transfer reaction, since the lifetime of an excited state is typically 10^{-12} s. Assuming the velocity of ^{67}Ni is $0.070c$, then the traveled

distance before its decay is about $21 \mu\text{m}$. The γ decay will thus be observed by the Miniball detectors. The prompt coincidence window is chosen to cover the center peak in figure 4.6 at $-200 < t_d - t_\gamma < 175 \text{ ns}$. The width of the prompt peak in the time-difference spectrum is due to the time resolution of the detectors, in particular the Ge detectors. The signal processing time increases with increasing γ energy. The constant background is due to random coincidences of deuterons with γ rays, most prominently with the 1039 keV γ ray from the β decay of ^{66}Cu .

Besides prompt decaying excited states there can be isomeric states², in ^{67}Ni there is such a state at 1007 keV with a half-life of $13.3(2) \mu\text{s}$ [Gea98]. Since it takes only about $0.1 \mu\text{s}$ for ^{67}Ni to reach the beamdump chamber, the decay of this state cannot be observed in the Miniball detectors but will be studied with the coaxial Ge detector at the beamdump.

Doppler Correction

As a consequence of the high velocity of the ^{67}Ni nuclei, the measured γ energies will be Doppler shifted. The measured γ energy will not correspond to the energy difference between the initial and final levels involved³ in the transition. In the analysis this effect is corrected for by:

$$E_0 = \sqrt{1 - \beta^2}(1 - \beta \cos \xi) E_{\text{lab}}, \quad (4.2)$$

where $\beta = v/c$, E_{lab} is the measured gamma energy in the lab frame, E_0 is the gamma energy in the frame where the decaying nucleus is at rest, and ξ is the emission angle of the γ ray with respect to the velocity direction of the emitter A . The emission angle ξ can be obtained via

$$\cos \xi = \sin \theta_A \cos \theta_\gamma \cos (\phi_A - \phi_\gamma) + \cos \theta_A \cos \theta_\gamma \quad (4.3)$$

where (θ_A, ϕ_A) and $(\theta_\gamma, \phi_\gamma)$ are the polar and azimuthal lab angles of ^{67}Ni and the γ ray respectively. The angle of the γ ray is measured by the segmented Miniball detectors. The polar and azimuthal angle of ^{67}Ni differs at most 2.1° from the beam direction, since this particle is not detected in the setup this angle is approximated to be zero. Expression (4.3) then reduces to $\cos \xi = \cos \theta_\gamma$. Relativistically, the β -value can be calculated from the kinetic energy of ^{67}Ni ,

$$\beta = \frac{\sqrt{E_A(E_A + 2m_A c^2)}}{E_A + m_A c^2}, \quad (4.4)$$

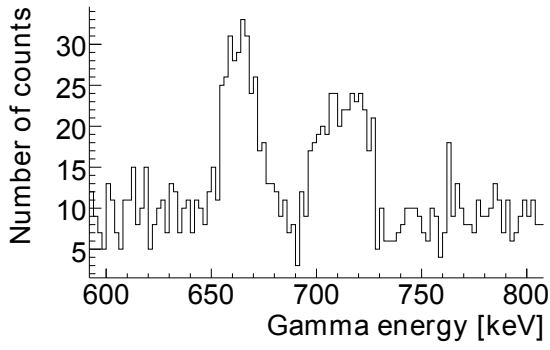
where E_A and m_A are the kinetic energy and mass of ^{67}Ni . From conservation of energy in the reaction one can obtain the kinetic energy of ^{67}Ni via

$$E_A = E_{\text{beam,lab}} + Q - E_{\text{excitation}} - E_d, \quad (4.5)$$

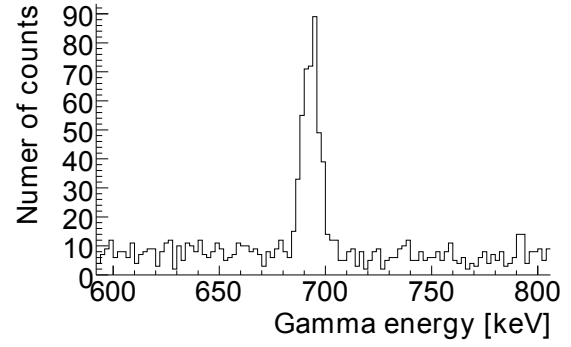
where $E_{\text{beam,lab}}$ is the beam energy in the middle of the target, E_d is the energy of the deuteron which is detected in prompt coincidence with the γ ray, and $E_{\text{excitation}}$ is the

²An isomeric state is a metastable excited state with a half life that is 10^2 to 10^9 times the half life of a typical prompt excited state.

³When an excited nucleus at rest emits a γ ray, then the energy difference between the initial and final level is equal to the sum of the γ ray energy and the recoil energy of the nucleus. This recoil energy is in the order of a few eV for a 1 MeV transition and is a lot smaller than the energy resolution of the detector. This energy difference is negligible compared to the Doppler shift when the excited nucleus moves with a high velocity in the lab frame.



(a) 693.4 keV peak without Doppler correction.



(b) 693.4 keV peak with Doppler correction.

Figure 4.7: The spectrum on the left shows the γ energy of the 693.4 keV from the decay of ^{67}Ni as detected by the Miniball detectors without Doppler correction. The graph on the right shows the Doppler corrected spectrum. All γ rays in this spectrum are in prompt coincidence with a deuteron.

excitation energy of ^{67}Ni which can be deduced from the deuteron energy. For each d - γ event β is calculated and used in equation (4.2) to correct the energy of the γ ray. For example the FWHM of the 693.4 keV γ ray in figure 4.7 is 10 keV when Doppler corrected, without the Doppler correction there are two peak with a FWHM of about 30 keV centered around 665 keV and 710 keV corresponding to the gammas measured with the gamma detectors in backward and forward direction respectively.

d - γ Events

Each deuteron- γ event is a fingerprint of the (t, d) reaction. Of each event the corresponding deuteron energy and γ energy is measured. From the deuteron energy one can calculate the excitation energy of ^{67}Ni . This information is combined in figure 4.8 where the excitation energy of ^{67}Ni versus the γ ray energy is plotted.

This figure is very rich in information on the internal structure of ^{67}Ni . One great feature is that one can determine how the initial level of the γ transition was fed, this can either be directly by the transfer reaction or from the decay of higher lying excited states. Consider figure 4.9 where the low excited states of ^{67}Ni that are observed in this experiment are shown (with in addition the isomeric state at 1006.6 keV).

When the 1724.3 keV excited state is populated by the transfer reaction (dashed line) it decays to the ground state. The 1724.3 keV γ ray can also be emitted as a result from the feeding of the 2207.4 keV state in ^{67}Ni (dotted line) followed by the 483.1 keV γ decay to the excited state at 1724.3 keV. These two pathways can be discriminated from one-another in the excitation energy vs γ energy plot in figure 4.8. From conservation of energy it follows that a deuteron from the transfer reaction to the 1724.3 keV excited state is more energetic than the deuteron from a transfer reaction to the 2207.4 keV excited state when they are emitted in the same direction. The situation sketched with the dashed line in figure 4.9 will result in d - γ events at the intersection of $E_\gamma = 1724$ keV and the drawn black line. The situation sketched by the dotted line corresponds to an excitation energy of 2207.4 keV, indeed in figure 4.8 events with $E_\gamma = 1724$ extend up

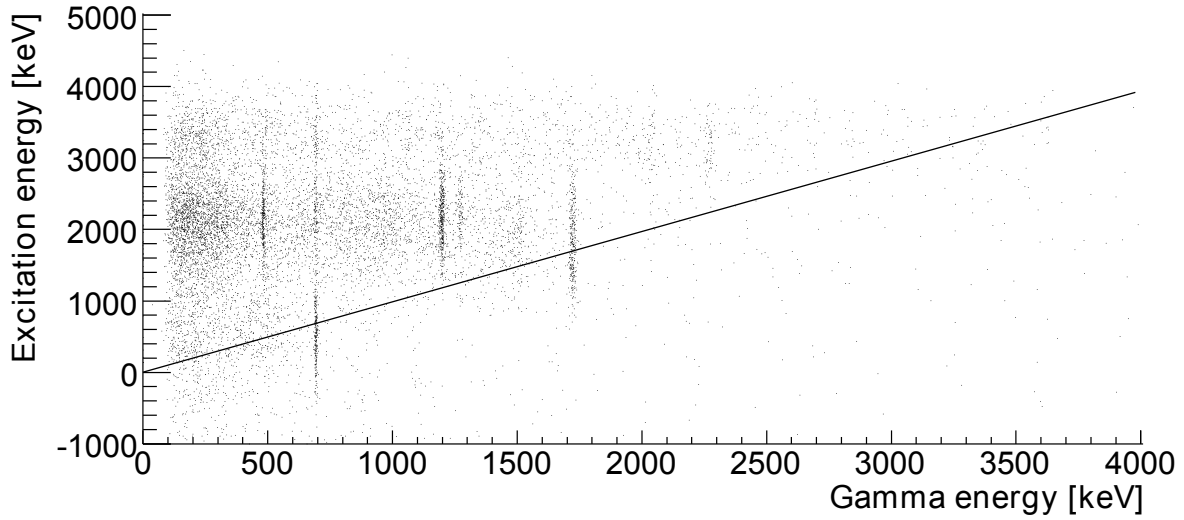


Figure 4.8: The γ ray energy and the excitation energy of ^{67}Ni deduced from the deuteron energy of prompt d - γ events. The line corresponds to $E_\gamma = E_{\text{excitation}}$, and represents transitions directly to the ground state.

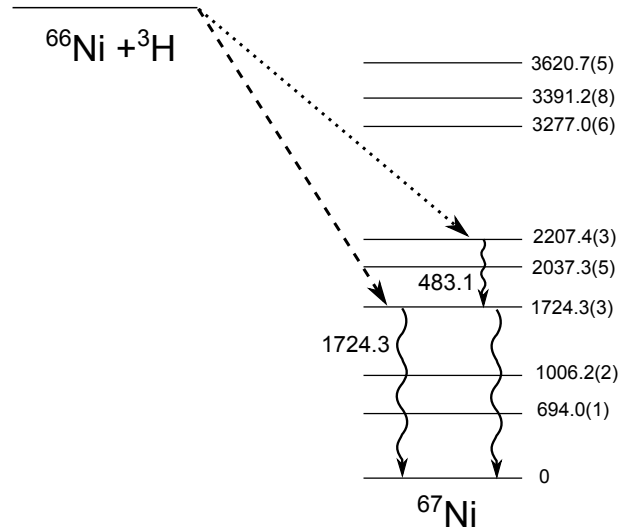


Figure 4.9: This figure illustrates how the emission of a γ ray, here 1724 keV, can result from direct feeding via the transfer reaction (dashed line) or via the decay of a higher lying excited state (dotted line). The excited states from which γ rays are observed in this experiment are shown, also the isomeric state at 1006.6 keV which is taken from [Dir13] is drawn. All energy values in keV are taken from the study of the $^{66}\text{Ni}(d,p)^{67}\text{Ni}$ transfer reaction studied by J. Diriken [Dir13].

to high excitation energies. In the case of the 694 keV γ ray this feature is even more clear. There the population of excited states around 3.2 MeV, 2.2 MeV and 700 keV can be observed. From figure 4.8 one cannot investigate the population of the ground state and isomeric state, both cases will be discussed later. The next section of this chapter the analysis of the γ rays will be discussed, the following section will be dedicated to the energy of the deuterons and the excitation spectrum.

4.3 Gamma Spectrum

The measurement of γ rays is crucial to investigate the internal level structure and to accurately identify the different reaction channels. The gamma spectrum as detected by Miniball without Doppler correction is shown in figure 4.10.

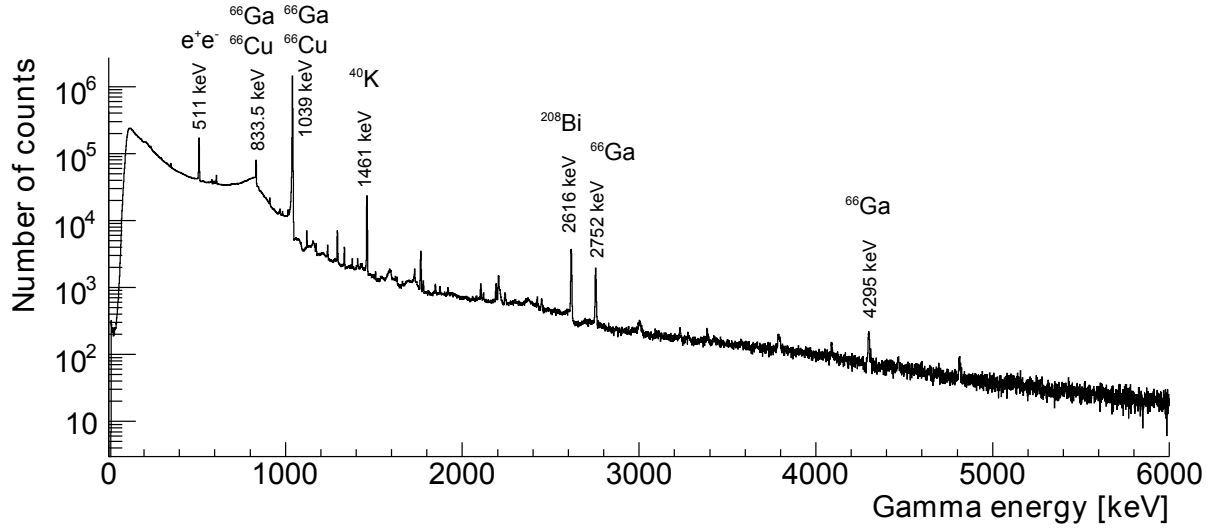


Figure 4.10: Gamma spectrum measured with Miniball.

The spectrum is dominated by the 1039 keV γ ray from the β decay of ^{66}Cu to ^{66}Zn ($Q = 2.1$ MeV). This decay is observed since the ^{66}Ni beam is partially stopped in the target chamber and decays to the ground state of ^{66}Cu . The peak at 833.5 keV is another γ ray from the decay of ^{66}Cu . The peaks at 2752 keV and 4295 keV originate from the decay of ^{66}Ga to ^{66}Zn ($Q = 5.17$ MeV). In fact the decay of ^{66}Ga also contributes to the peaks at 833.5 keV and 1039 keV. This observation shows that the ^{66}Ni beam is contaminated with a small amount of ^{66}Ga , less than 1%. The spectrum also contains γ rays of ^{40}K and ^{208}Bi which are long-lived isotopes that are present in the experimental hall in ISOLDE. The peak at 511 keV originates from electron-positron annihilation. These γ rays are not of interest in this study. They are filtered out in the analysis by imposing γ -particle coincidence conditions.

4.3.1 Prompt and Random Coincidence Windows

The Doppler corrected prompt deuteron- γ spectrum is shown figure 4.11.

The random coincidence window includes all events that lie outside the prompt coincidence window. It is instructive to compare both spectra to identify background γ rays that may still be present in the prompt coincidence gamma spectrum. The centroid, peak content and intensity of the observed γ rays are listed in table 4.1.

All peaks are fitted with a Gaussian curve imposed on a linear background. The intensity of each peak is calculated by dividing the number of counts by the absolute efficiency at the centroid. The listed γ rays have also been observed in the $^{66}\text{Ni}(d,p)^{67}\text{Ni}$ reaction, the proposed level scheme of ^{67}Ni from this (d,p) reaction studied by J. Diriken [Dir13] is shown in figure 4.12.

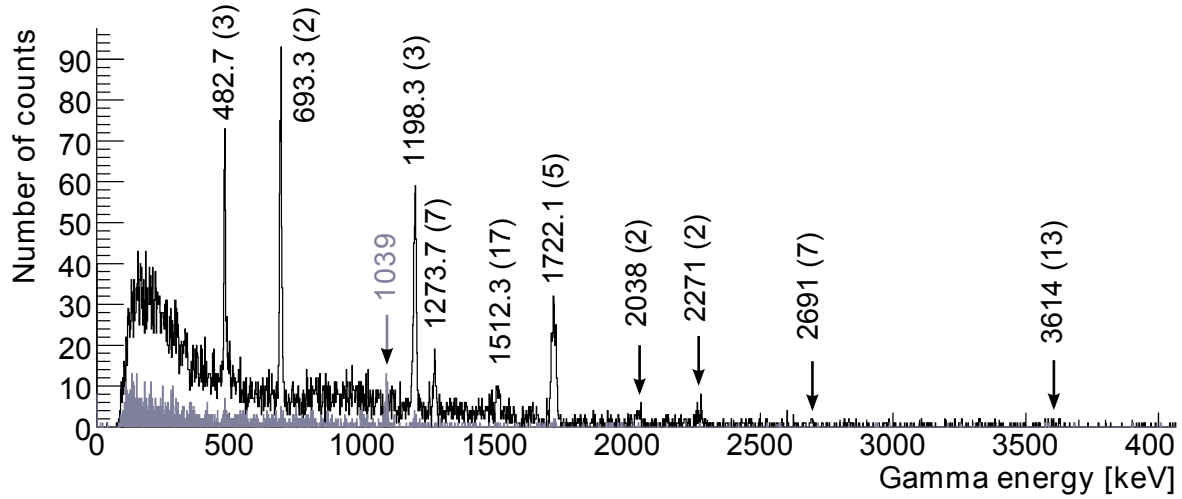


Figure 4.11: Doppler corrected gamma spectrum of γ rays in prompt (black) and random (grey) coincidence with deuterons passing through the ΔE detector detected with Miniball.

Table 4.1: Centroid, peak content and intensity of the peaks observed in the d - γ coincidence spectrum shown in figure 4.11.

Centroid [keV]	Peak content	Intensity [%]
482.7 (3)	249 (34)	10 (2)
693.3 (2)	389 (33)	19 (2)
1198.3 (3)	402 (34)	26 (3)
1273.7 (7)	78 (15)	5 (1)
1512.3 (17)	65 (21)	5 (1)
1722.1 (5)	300 (27)	24 (3)
2038 (2)	41 (12)	4 (1)
2271 (2)	50 (15)	5 (1)
2691 (7)	11 (6)	1 (1)
3614 (13)	11 (6)	1 (1)

The γ rays and excited states that are observed in the analysis of the (t, d) reaction in this thesis are highlighted in blue. The γ energies listed in table 4.1 are in agreement with the values from the (d, p) reaction and literature [Jea05]. For several low intensity, high energetic γ rays the energy measured in this experiment deviates from the literature values due to the low statistics, the error on the energy of these γ rays is large.

There is one γ ray of 1273.7(7) keV that could not be placed in the level scheme, this γ ray has also been observed in the (d, p) reaction. Attempts were made to find correlations of this γ ray with other γ transitions by means of d - γ - γ coincidence measurements, these will be discussed later.

4.3.2 Direct Level Population in the (t, d) Transfer Reaction

From the intensity of the γ rays the feeding of excited states which decay by prompt gamma emission can be obtained. One can calculate the feeding by:

$$\sum_{\text{out}} I_{\gamma} - \sum_{\text{in}} I_{\gamma}, \quad (4.6)$$

where the first sum runs over all γ rays leaving the level that is considered and the second sum runs over all γ rays that feed this level. For instance in the case of the 1724 keV level, there is only one γ ray leaving this level, if we assume the transition to the 694 keV state is negligible. There are five γ rays populating this state namely 483.1, 1552.7, 1666.9, 1896.4 and 2138.7 keV. Since only the 483.1 keV γ ray is observed we assume the 1724 state is only populated by this γ ray and of course the transfer reaction itself. The feeding of the 1724 keV level can then be approximated by $I_{1724} - I_{483.1}$. In table 4.2 the relative level feeding of the prompt γ -decaying observed states in ^{67}Ni are given.

Table 4.2: Relative feeding of the energy levels deduced from γ ray intensities scaled to the feeding of the 2207.4 keV state.

Energy [keV]	Feeding [a.u.]
694	32 (8)
1724.3	33 (9)
2037.5	9 (3)
2207.4	100 (14)
3277	11 (4)
3391	2.7 (15)
3620	3 (2)

This description works for all γ decaying states. However to determine the feeding of the isomeric state the same approach can be used but the intensity of the γ ray leaving this state has to be determined from the decay in the beamdump since the isomeric state does not decay in the target chamber. This case will further be discussed in subsection 4.3.4.

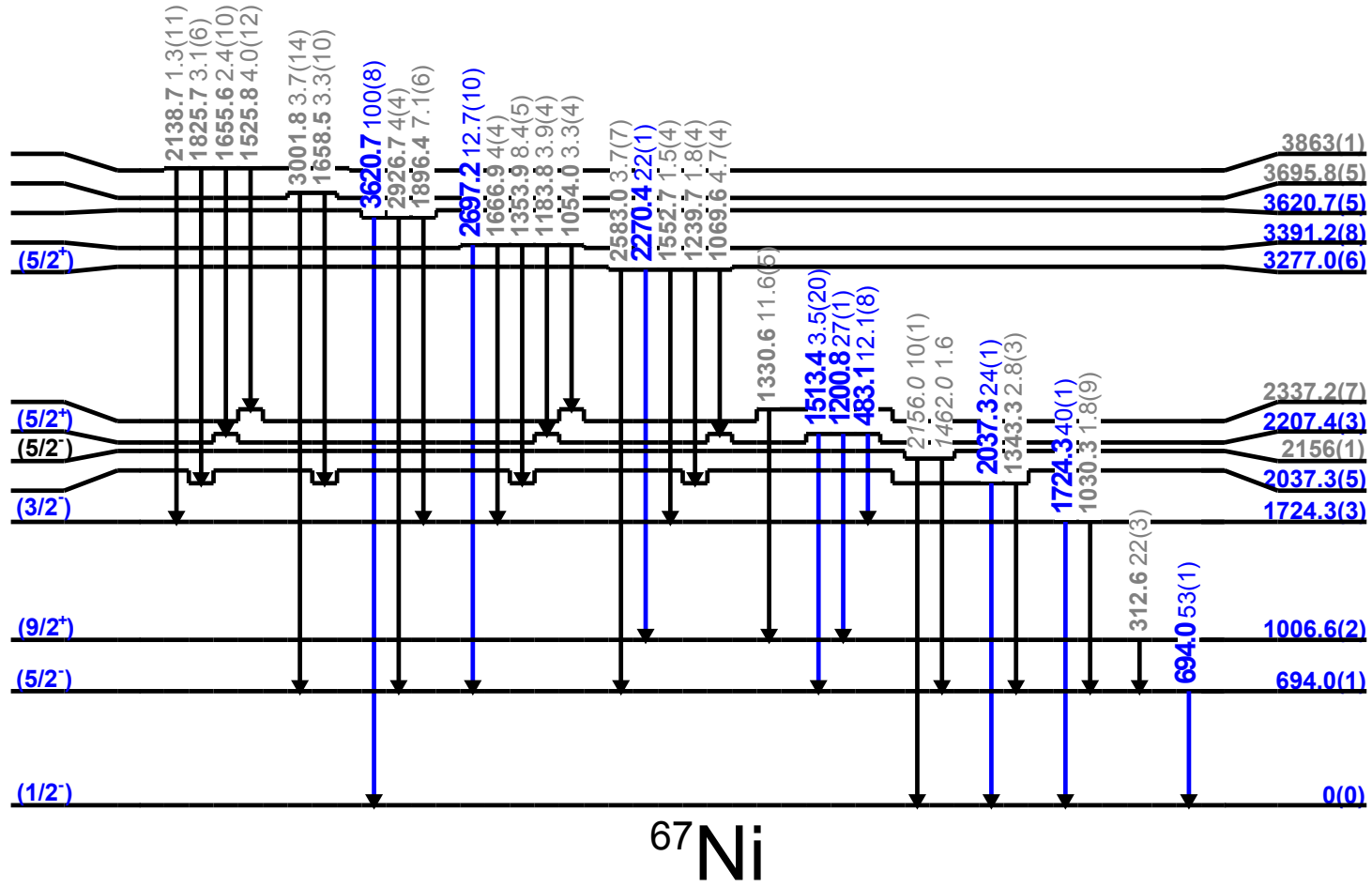


Figure 4.12: The level scheme of ^{67}Ni for low energies from the $^{66}\text{Ni}(d, p)^{67}\text{Ni}$ reaction studied by J. Diriken, all energies, intensities and spins are taken from [Dir13]. The 1006.6 keV state is an isomeric state with a half-life of $13.3(2) \mu\text{s}$ [Gea98]. The numbers highlighted in blue correspond to energy levels and γ rays that are observed in the (t, d) reaction in this thesis.

4.3.3 d - γ - γ Coincidences

Deuteron- γ - γ coincidences are an important tool to investigate the level structure of ^{67}Ni . Coincident gammas arise from the decay of sequential energy levels. For instance γ_1 from the first excited state to the ground state is in coincidence with any γ_i directly or indirectly feeding the lowest excited state when the lifetime of the energy levels involved is significantly shorter than the prompt coincidence window. The prompt γ - γ coincidence window is: $-225 \text{ ns} < t_{\gamma_1} - t_{\gamma_2} < 225 \text{ ns}$. In this section the analysis procedure will be described.

A four step procedure is followed to construct d - γ - γ spectra. Consider the case where one wants to select all γ_i that are in coincidence with γ_1 , which in turn is in prompt coincidence with a deuteron.

The first step in the procedure is to create the spectrum of all γ rays in prompt coincidence with a deuteron, this was discussed in section 4.3.1 and shown in figure 4.11.

In the second step one chooses an energy interval comprising the photopeak of γ_1 in the d - γ spectrum. In addition, two energy intervals are constructed, one on the left and one on the right side of the γ_1 photopeak as shown in figure 4.13. These intervals will serve to describe the linear background of the γ_1 peak.

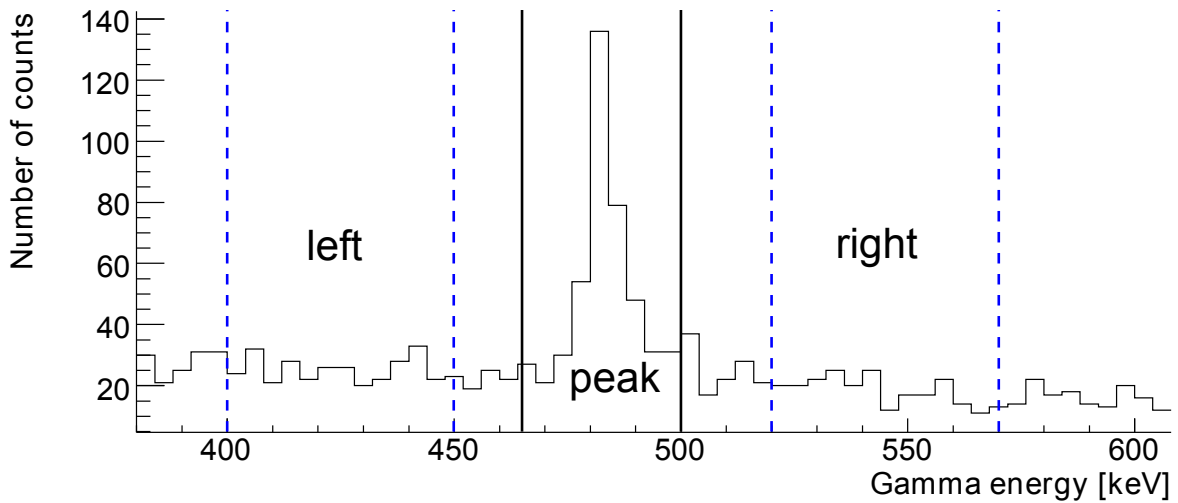
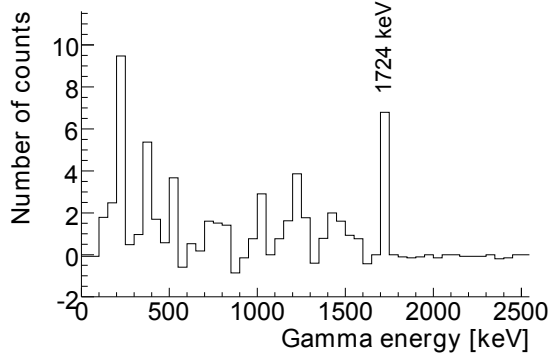


Figure 4.13: The solid lines indicate the interval covering the 483 keV peak, the blue dashed lines show the right and left intervals for construction of a spectrum of γ rays in coincidence with a deuteron and the 483 keV γ ray.

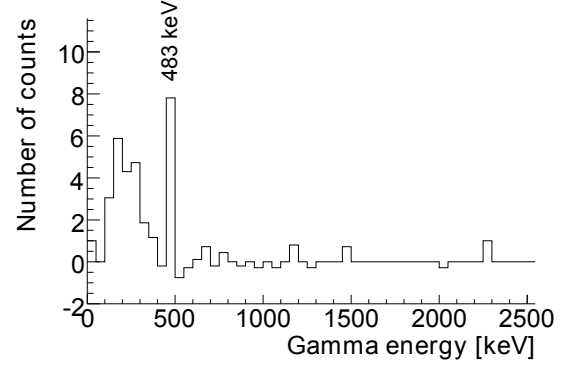
For each of these intervals all γ rays in prompt coincidence and all γ rays that are not in prompt coincidence (random spectrum) are constructed. Subsequently the random spectrum is scaled to the time-width of the prompt spectrum and subtracted from the prompt spectrum to exclude random events in time.

As a final step the Prompt-Minus-Random spectrum (PMR) of the energy intervals on the left and on the right side are scaled to half the energy width of the peak interval and subtracted from the PMR spectrum of the peak. These rescaled PMR spectra of the left and right intervals represent coincidence events originating from the background on

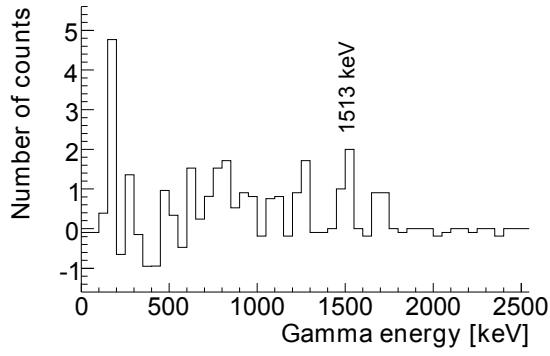
which the γ_1 photopeak on is situated. In figure 4.14 d - γ - γ spectra for different γ rays are shown.



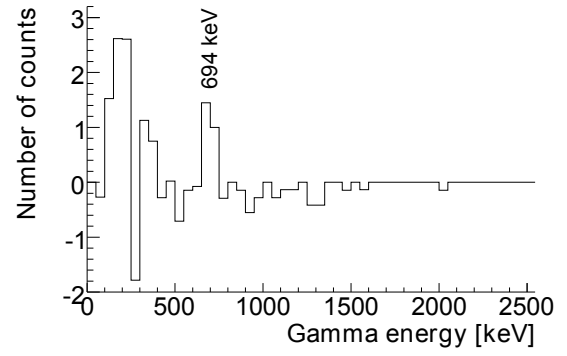
(a) Gate on 483 keV



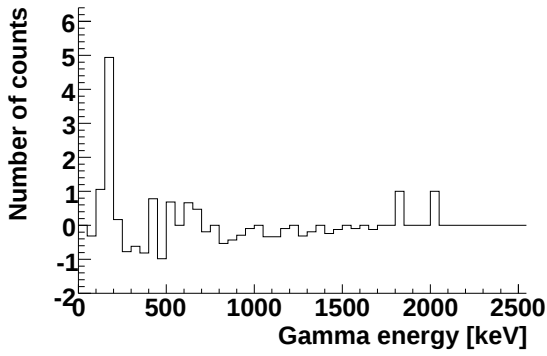
(b) Gate on 1724 keV



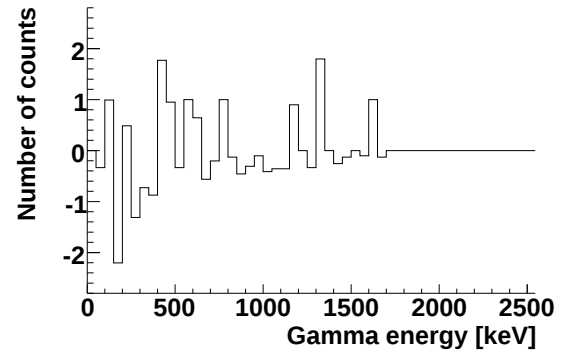
(c) Gate on 694 keV



(d) Gate on 1513 keV



(e) Gate on 1198 keV



(f) Gate on 1274 keV

Figure 4.14: d - γ - γ coincidence spectra gated on different gamma transitions.

The statistics in all figures are low which limits us to the observation of only a few coinci-

dent gamma rays. At low energies the procedure does not fully exclude the background. Two coincident γ rays are found in figures 4.14a and 4.14b, namely the 483 keV is in coincidence with the 1724 keV γ ray. A second indication of a coincident pair of γ rays is found figures 4.14c and 4.14d. The latter shows a small peak which may correspond to the 694 keV transition, also in the 694 keV gated spectrum a small peak around 1513 keV is observed. This indicates both γ rays are in coincidence. These observations are in agreement with the level scheme in figure 4.12.

The 1274 keV gated spectrum has also been constructed (see figure 4.14f), unfortunately no coincident γ rays are observed. Even though the relative intensity of this γ ray (22(5)) is higher than the intensity of the 1513 keV (14(4)), where a weak indication of the coincident 694 keV γ is present.

Also a 1198 keV gated d - γ - γ spectrum has been constructed (see figure 4.14e), no coincident γ rays from higher lying excited states can be found. There is one notable peak around 180 keV, this is due to the high background at low energies and large bin width (50 keV/bin). From the level scheme in figure 4.12 the 1198 keV gamma ray feeds the isomeric state at 1007 keV which mainly decays to the 694 keV state by via a 313 keV γ ray. The half life of the isomer is 13.3(2) μ s [Gea98] and can not be observed with the Miniball detectors. In the following the analysis of the isomeric decay will be further discussed.

4.3.4 Slow Coincidences

From literature the isomeric state in ^{67}Ni is tentatively assigned to be a spin $9/2^+$ state at 1007 keV [Pea94], and has a half life of 13.3(2) μ s [Gea98]. This state mainly decays to the $(5/2^-)$ state at 694.1 keV [Wea04], which is an $M2$ or $E3$ transition, the decay to the $(1/2^-)$ ground state [Rea83] is extremely weak as this is an $M4$ or $E5$ transition, from the Weisskopf estimates⁴ the $M4$ transition probability is 10^{-8} times smaller than the $M2$ transition probability. The decay of the isomer can not be observed with the Miniball detectors since all ^{67}Ni nuclei will have left the target chamber before the isomeric state decays. In order to study the decay of μ s isomers the setup is equipped with a beamdump chamber. At about 2 m from the target chamber the beam-like particles are implanted in a thick aluminum foil. With a coaxial germanium detector the emitted γ rays are detected.

The measured γ spectrum is dominated by the β decay of ^{66}Cu to ^{66}Zn . To obtain a cleaner spectrum only γ rays that are detected together (within a certain time window) with a deuteron in the T-REX silicon detector are selected. Of course this time window can not be set as narrow as for d - γ coincidences detected with Miniball since the γ rays from the isomer would not be observed. We consider a *slow coincidence* time window of 80 μ s such that events with $0 < t_\gamma - t_d < 80 \mu\text{s}$ are registered. Within this time window, covering about 6 times the half-life, it is possible to detect the isomeric decay. This has been verified in the (d, p) experiment [Dir13]. From the d - γ spectrum from this experiment (figure 4.15a) however it is not possible to observe the isomeric decay because of the low statistics. Only the 511 keV peak from electron-positron annihilation and the 1039 keV from ^{66}Cu are clearly present.

More stringent conditions can be imposed, one can select only those γ rays in the beam-

⁴The Weisskopf estimates of the $M2$ and $M4$ transition that are used are $\lambda(M2) = 3.5 \frac{25}{16} 10^7 A^{2/3} E^5$ and $\lambda(M4) = 4.5 \frac{36}{49} 10^{-6} A^2 E^9$ from [Kra88].

dump which are in slow coincidence with a deuteron which in turn is in prompt coincidence with the 1198 keV detected by Miniball. This 1198 keV transition is the most intense transition feeding the isomeric state. Unfortunately, again, the 313 keV γ ray could not be observed. This d - γ - γ spectrum is given in figure 4.15b. The peak around 850 keV is not a real peak but a consequence of the large width of the bins in the spectrum (50 keV/bin). The number of expected 313 keV decays can be estimated using the transmission efficiency and detection efficiency of the beamdump detector from the PhD thesis of J. Diriken [Dir13]. The efficiency in this experiment will be different from the (d, p) reaction in [Dir13] but is expected to be similar. The transmission efficiency (from the target chamber to the aluminum foil) is 59(8)% and the absolute photopeak efficiency of the detector for the 313 keV gamma is 7.4%. The beamdump chamber was active for 56.5% of the total runtime. From the number of 1198 keV gamma rays detected in the Miniball detector, one expects to detect at least 5 counts in the beamdump detector. With these low statistics the decay of the isomeric state could not be studied. Consequently the feeding to the isomeric state could not be determined.

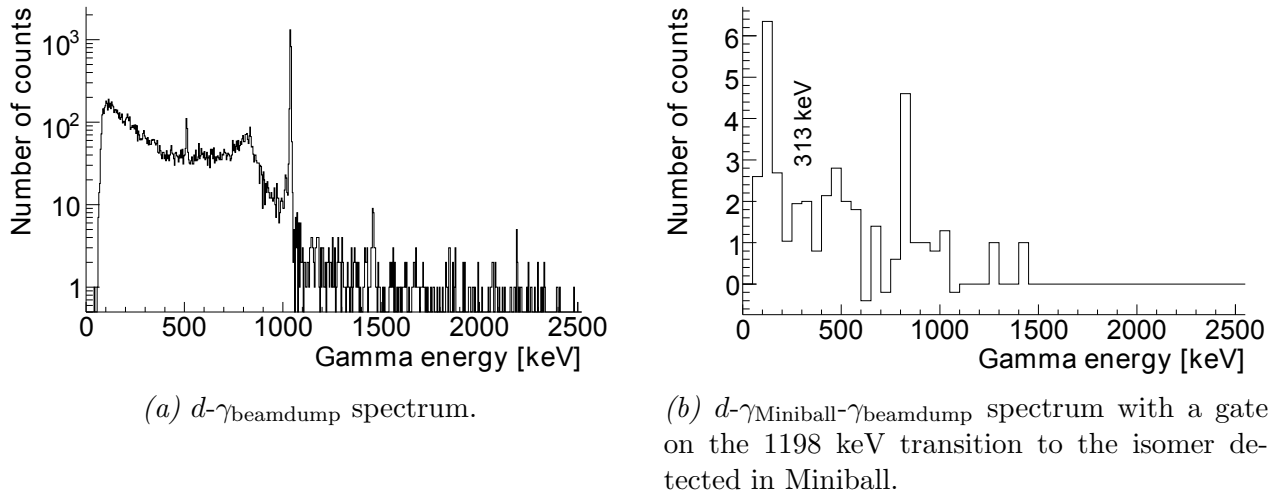


Figure 4.15: Gamma spectra from the beamdump coaxial detector for d - γ_{beamdump} slow coincidence events (a) and d - γ_{Miniball} - γ_{beamdump} events (b) where d - γ_{Miniball} is in prompt coincidence and γ_{beamdump} in slow coincidence. The spectrum on the right has been constructed using the PMR procedure as discussed in section 4.3.3.

4.4 Excitation Spectrum

Up to now only the γ rays from ^{67}Ni have been discussed, of course also the energy of the deuterons provides valuable information on the populated excited states. From kinematic considerations the energy of the populated excited states can be calculated as the deficit energy of the deuterons with respect to a transfer reaction to the ground state. In this section we focus on the deuterons to get more insight in the level structure of ^{67}Ni . The black curve in figure 4.16 shows the excitation spectrum of ^{67}Ni .

If the incident beam had a very precise energy and the detection system was perfect than each excited state would show up as a sharp line in the spectrum. However the beam has

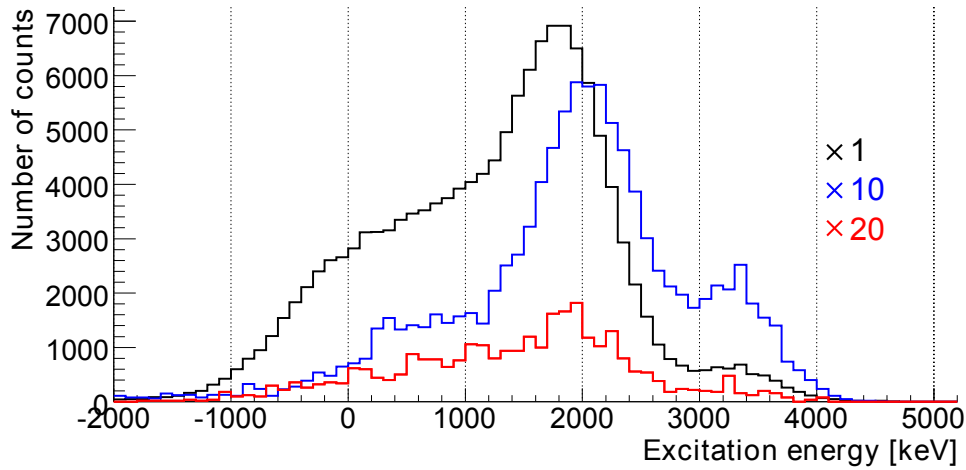


Figure 4.16: This figure shows the excitation spectrum of ^{67}Ni . The black curve includes deuterons that pass through the ΔE detector and are stopped in the pad detector. The blue curve includes these deuterons that are in prompt coincidence with a γ ray. The blue curve is scaled by a factor 10. The red curve shows deuterons in random coincidence with a γ ray, scaled by a factor 20.

a finite energy spread and straggles in the $500 \mu\text{g}/\text{cm}^2$ thick target, consequently there is a spread in the energy of the beam at the reaction point. This is the main contribution to the poor resolution. Furthermore also the emitted deuterons straggle in the target and in the Mylar foil and the detectors have a certain energy resolution. As a result the excited states in the excitation spectrum appear as broad peaks [Win97]. Simulation with GEANT4 [Aea03] show that the FWHM of the excitation peaks ranges from 1 MeV to 700 keV for ground state and the 3.6 MeV excited state. This effect is even larger for heavier beams and heavier emitted particles. By decreasing the target thickness one can increase the resolution but consequently the number of reactions will decrease since there are less target atoms. One can also decrease the foil thickness but then scattered heavy particles will not be stopped.

The red curve in figure 4.16 shows all deuterons that pass through the ΔE detector and are in random coincidence with a γ ray. The blue curve shows all deuterons that pass through the ΔE detector and are in prompt coincidence with a γ ray. This spectrum can be obtained by projecting the data in figure 4.8 on the y -axis. This curve does not include deuterons from transfer reactions to the ground state nor to the isomeric state. The difference in shape of this curve and the black curve can thus be assigned to the feeding of the ground state and the isomeric state. In principle one can reconstruct the excitation spectrum by introducing the feeding of the ground state and isomer by Gaussian curves with fixed centroid, FWHM and varying amplitude. However one can not obtain a single unique solution for the feeding of these two states since the FWHM is in the order of the energy separation of the ground state and isomeric state.

Besides the different shape due to the ground state and isomeric feeding the blue and black curves also do not match at higher energies, $> 1.5 \text{ MeV}$. For instance, in the excitation

spectrum (black curve) there is a peak at 1.8 MeV which does not coincide with the peak in the d - γ excitation spectrum (blue curve) at 2 MeV. The origin of these deuterons has been investigated.

Isomeric State at 1.8 MeV One possibility would be that there is an isomeric excited state at 1.8 MeV. This isomeric state would not show up in d - γ coincidence events. However no excited state in ^{67}Ni has been observed at 1.8 MeV besides the 1.724 MeV and 2037 keV states [Dir13, Pea94, Wea04, Gir88]. Moreover, from the number of counts around 1.8 MeV in the excitation spectrum, the unknown state would be the most populated state in ^{67}Ni . The fact that no γ rays feeding this isomer from the higher lying excited states are detected, points out the existence of such an isomeric state is doubtful. The 1274 keV γ ray, which cannot be placed in the level scheme in figure 4.12, cannot be a candidate either since this γ ray originates from populated excited states around 2.2 MeV as can be seen in figure 4.8. Furthermore there is a $(5/2^-)$ state at 2156 keV and $(5/2^+)$ states at 2207 keV and 3277 keV [Dir13]. The non-observation of γ transitions from this state to the isomer, points out that the spin of the isomeric state would have to be high ($13/2$ or more) to strongly hinder the transition. Such a high spin state is not expected to lie at this low energy.

(p, d) Reaction The target contains protons to the level of a few percent. Consequently deuterons may also originate from a (p, d) reaction. The Q -value of the $^{66}\text{Ni}(p, d)^{65}\text{Ni}$ reaction is -6.727 MeV. Since the CM energy is only 2.58 MeV the deuterons cannot be produced in this reaction.

$(^3\text{He}, d)$ Reaction Deuterons can also originate from the $^{66}\text{Ni}(^3\text{He}, d)^{67}\text{Cu}$ reaction with $Q = 3.1$ MeV. The number of ^3He nuclei builds up in the target from the decay of ^3H , the amount of ^3He is about $6.2 \mu\text{g}/\text{cm}^2$. The deuterons from this transfer reaction to the ground state of ^{67}Cu are much more energetic than deuterons from a $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ reaction to the ground state of ^{67}Ni . To mimic the (t, d) reaction to a 2 MeV state in ^{67}Ni , the $(^3\text{He}, d)$ reaction must populate a state in ^{67}Cu at 6 MeV. Consequently γ rays from ^{67}Cu should be observed, such as the 1115 keV γ ray from the first excited state to the ground state. This γ ray is not observed, it is thus not likely that the deuterons in the peak in black at 1.8 MeV in figure 4.16 stem from this reaction.

Elastic Deuteron Scattering A final possibility that was thought of is that these deuterons originate from elastic scattering of ^{66}Ni on deuterons in the target. This is certainly not expected since the target does not contain deuterons. In figure 4.2 the kinematic curve of elastically scattered deuterons is shown (solid red curve). A full calculation taking into account the thickness of the target, the foils, the detectors, etc. shows that the elastically scattered deuterons mimic deuterons from a (t, d) transfer reaction to an excited state at 1.6 MeV in ^{67}Ni . Thus if deuterons originate from both transfer reactions and elastic scattering then the distribution would be centered between 1.6 MeV and 2 MeV as is the case in figure 4.16. One way to test this hypothesis is to look at the random d - γ excitation spectrum (red curve in figure 4.16). Elastically scattered deuterons are independent of the time difference $t_d - t_\gamma$ while this timing is important for deuterons from a transfer reaction. In the random spectrum the number of deuterons from a transfer

reaction is much less than in the prompt spectrum. While the influence of the elastically scattered deuterons will not be affected by looking at different time windows. Hence in the random spectrum elastic scattered deuterons will show up more clear. One can indeed observe a broad structure around 1.8 MeV, unfortunately it is not possible to determine whether this peak corresponds to elastic scattering events or a transfer reaction since the energy lies in between 1.8 and 2 MeV. Furthermore if elastic scattering on deuterons occurs then the d - γ gamma spectrum may contains γ rays from inelastic scattering of deuterons on ^{66}Ni (such as 1424 keV) and this is not the case. This non-observation, on the other hand, does not exclude the possibility of elastically scattered deuterons since the cross section of this inelastic channel is much lower than the elastic channel. The specific origin of these deuteron events has not been found yet.

4.5 Angular Distributions and DWBA Calculations

In this section the analysis of the angular distribution of deuterons from the (t, d) transfer reaction and tritons from the elastic reaction channel will be presented. The obtained experimental results will be compared to DWBA calculation performed with Fresco [TN09]. The differential cross section can be calculated as

$$\frac{d\sigma}{d\Omega} = \frac{Y}{I\Delta t N} \quad (4.7)$$

where Y is the number of particles detected in solid angle $d\Omega$, I is the average beam intensity, Δt is the total run time and N is the number of target atoms. The number of ^3H target atoms is known from the target characteristics given by the manufacturer, of course one must take into account the decay of ^3H . The total run time is known and the number of particles per solid angle $d\Omega$ can be found from the number of particles detected per strip in the barrel ΔE detector scaled by the detection efficiency of the setup. The average beam intensity I will be deduced from the elastic scattering channel.

4.5.1 Elastic Scattering and Determination of the Beam Intensity

In elastic scattering of ^{66}Ni on ^3H , tritons are scattered in forward direction up to 90° while ^{66}Ni only deviates 2.6° from the beam axis. In the T-REX setup only the scattered tritons are detected. To obtain the total number of tritons Y scattered in solid angle $d\Omega$, the particle detection efficiency of the detector must be taken into account. The particle detection efficiency of the barrel detector depends on the energy of the incoming particle and the scattering angle or strip number. In addition some tritons are lost in the particle identification of the data. In the ΔE - E plots the tritons partially overlap with deuterons. The graphical cuts are taken such that the number of deuterons in the interval covering the tritons is minimal and vice versa. This way some particles are lost. The total elastic triton detection efficiency of the forward barrel detector and data analysis was determined with GEANT4 simulations and is about 60%. This is rather low since only 3 of the 4 quadrants of the forward barrel detector are operational. The number of tritons detected per strip is scaled with the total elastic triton detection efficiency to obtain the total number of tritons per lab angle $Y(\theta)$.

The average beam intensity I can be obtained by comparison of the data with calculation of $\frac{d\sigma}{d\Omega}$. Calculations of the elastic scattering channel have been performed with Fresco [TN09] wherein global optical model parameters (OMP's) were taken from Li et al. [Lea07] and Becchetti and Greenlees [BG69, PP76]. In table 4.3 OMP's from the mentioned studies are given, for the shape of the optical model potential see chapter 3.

Table 4.3: OMP's from Li et al. [Lea07] and Becchetti and Greenlees [BG69] for the entrance channel ($^{66}\text{Ni} + t$), and for the exit channel of elastic scattering. OMP's from Han et al. [Cea09] to describe the transfer reaction exit channel ($^{67}\text{Ni} + d$). V and W represent the amplitudes of the real and imaginary components respectively. The parameters r and a are the range and the diffuseness of the interaction, subscript r refers to a real component and i to an imaginary component.

	Nuclear volume						Nuclear surface			Spin-orbit					
	V	r_r	a_r	W	r_i	a_i	W	r_i	a_i	V	r_r	a_r	W	r_i	a_i
	[MeV]	[fm]	[fm]	[MeV]	[fm]	[fm]	[MeV]	[fm]	[fm]	[MeV]	[fm]	[fm]	[MeV]	[fm]	[fm]
[Lea07]	162.4	1.1	0.8	10.6	1.3	1.2	25	1.1	0.9	1.9	0.5	0.1	0		
[BG69]	162.7	1.2	0.7	26.8	1.4	0.8	0			2.5	1.2	0.7	0		
[Cea09]	82.6	1.2	0.8	1.2	1.6	0.9	13.3	1.3	0.6	3.7	1.2	0.8	-0.2	1.2	0.8

The differential cross section of both models is shown in figure 4.17 as the ratio to the Rutherford scattering cross section.

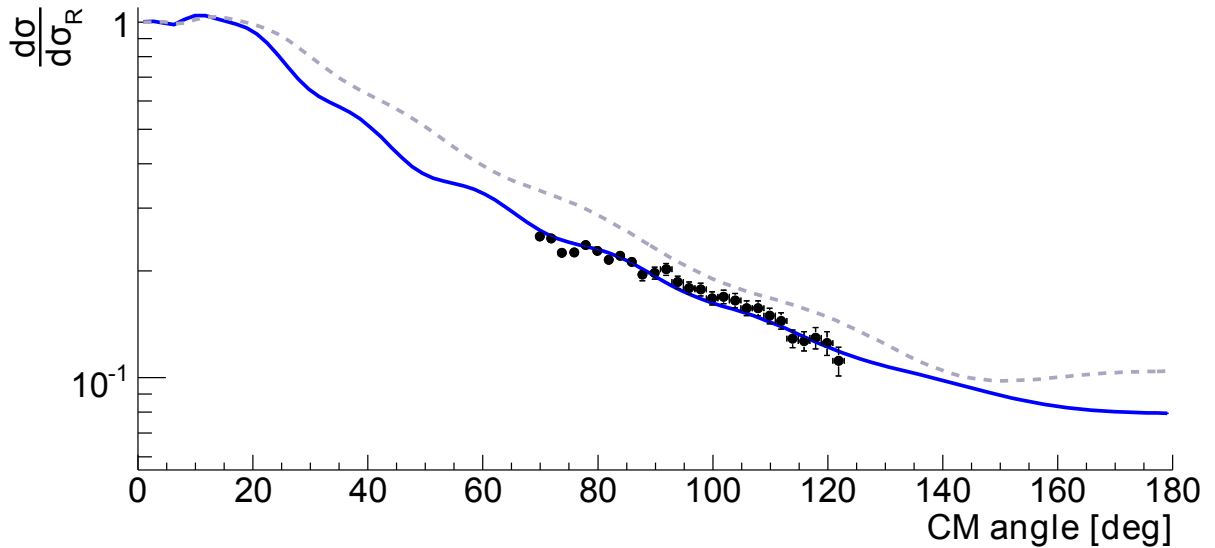


Figure 4.17: The experimental and calculated differential cross section of elastically scattered tritons. The blue curve shows the calculation performed with OMP's from Becchetti and Greenlees [BG69], the dashed grey curve uses OMP's from Li et al. [Lea07]. This is not a fit, the data points are rescaled by the factor $I\Delta tN$ obtained from the calculations of Becchetti and Greenlees.

The shape of the calculated differential cross section with OMP's from Becchetti and Greenlees corresponds best to the experimental data. These OMP's are also recommended

in [Cea09] and will be used in further calculations. The optical model calculations for elastic scattering offer reliable differential cross sections. This allows to scale the calculated differential cross section to the experimental angular distribution $Y(\theta)$ and obtain the value of $I\Delta tN$. From this the average beam intensity I can be deduced, namely $2.5(3) \cdot 10^6$ pps. In figure 4.17 the data points are scaled using the beam intensity deduced from OMP's from Becchetti and Greenlees.

4.5.2 $^{66}\text{Ni}(t, d)$ Transfer Reaction Channels

Now that the beam intensity is known it is possible to normalize the experimental angular distribution and calculate the absolute differential cross section of the transfer reaction channels. In the analysis four states of ^{67}Ni are considered, namely the ground state and excited states at 964, 1724 and 2207 keV.

Excited States

The angular distribution of deuterons from transfer reactions to the levels at 694 keV, 1724 keV and 2207 keV has been obtained by imposing two conditions on the (t, d) data. First of all only deuterons for which $|E_{\text{exc}} - E_{\text{exc}}^i| < 500$ keV are selected, where E_{exc} is the energy of considered excited state in ^{67}Ni and E_{exc}^i is the excitation energy of ^{67}Ni corresponding to a deuteron i . This interval covers about 80% of the excitation peaks which are described by Gaussians with a FWHM of about 1 MeV as discussed in section 4.4. Secondly the deuterons have to be in prompt coincidence with a γ ray from the decay of the corresponding excited state. To remove background events, a similar PMR procedure is used as in section 4.3.3. A wide energy interval on the left and on the right of the γ peak was selected, deuterons in coincidence with these γ rays are rescaled to correspond to half the width of the desired γ peak and subtracted from the data. When the particle and gamma detection efficiency are taken into account the differential cross section can be calculated with equation 4.7 using the beam intensity obtained from the elastic channel. The results are shown in figure 4.18. The differential cross section of the 2207 keV state is obtained by gating on the 1198 keV γ ray.

The differential cross sections from the Fresco calculations are drawn to compare with the data. Global OMP's were taken from [BG69] for the triton entrance channel and from [Hea06] for the deuteron exit channels. The depth of the interaction potential is adjusted to reproduce the binding energy of the neutron in the populated state of ^{67}Ni . DWBA calculations have been performed for ℓ -values from 0 to 4. For the excited states, $\ell = 0$ is coupled with the intrinsic spin to a $1/2$ state. For $\ell = 1$ a parallel spin-orbit coupling is used, corresponding to the $p_{3/2}$ orbital. For $\ell = 2$ also a parallel coupling is assumed, corresponding to the $d_{5/2}$ orbital. The spin-orbit coupling of $\ell = 3$ is anti-parallel corresponding to the $f_{5/2}$ orbital. In all calculations the spectroscopic factor is fixed at 1.

The data are limited to high CM angles and lie far from the position of the first maximum. Since the strongest evidence of a certain ℓ -transfer is the position of the first maximum of the differential cross section, it is impossible to decide what ℓ -value has been transferred in the reaction from the available data. The data points can correspond to any ℓ transfer reaction, since in the region we are sensitive to, the differential cross section varies smoothly and does not differ strongly for different ℓ -values. In principle one can deduce

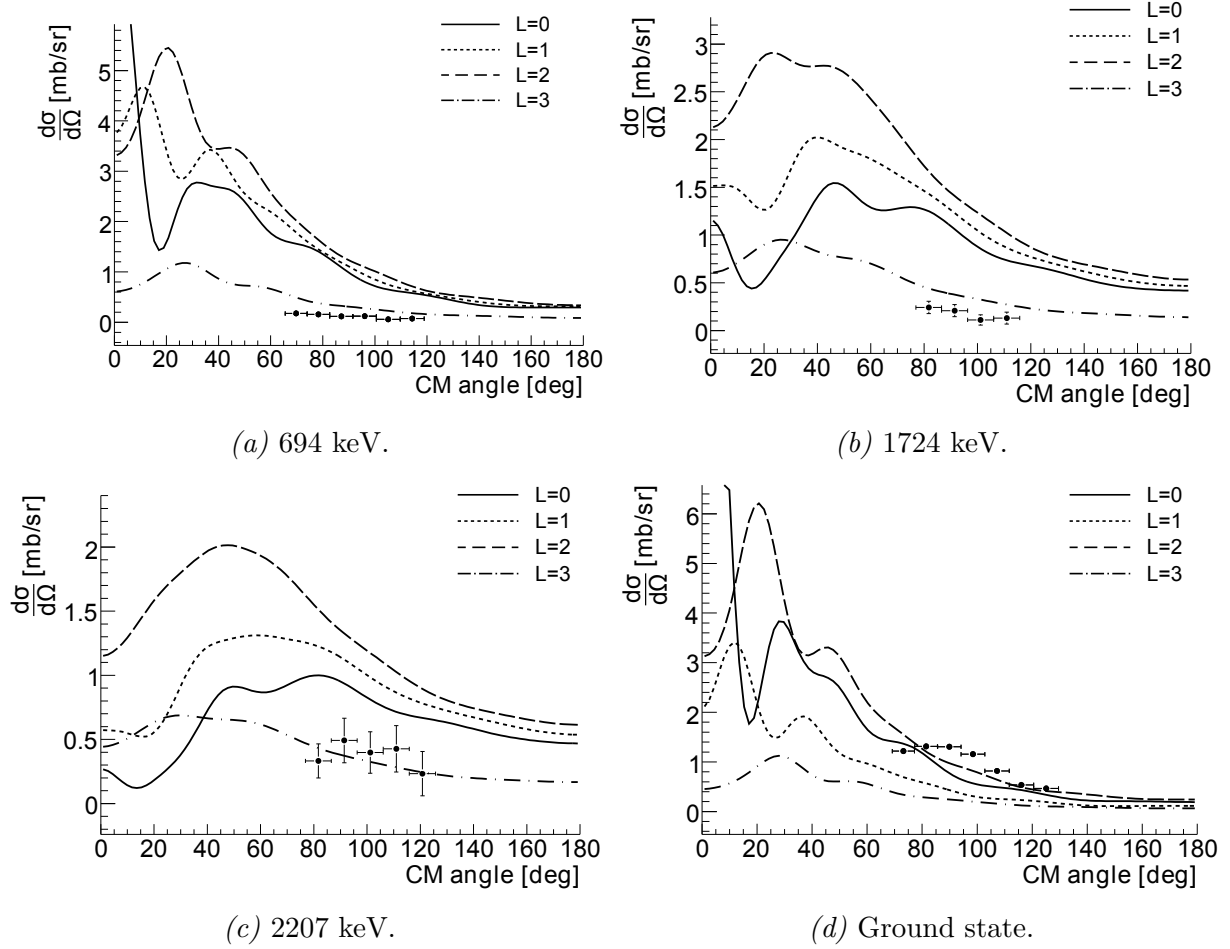


Figure 4.18: Differential cross sections of the (t, d) transfer reaction populating states in ^{67}Ni . The calculations have been performed with Fresco, assuming the spectroscopic factor is equal to one.

the relative spectroscopic factor SF by comparison of the theoretical calculations and experimental data. In this thesis the SF 's have not been determined. First of all since the correct ℓ -value can not be deduced. Secondly the approximations that are made in the DWBA theory are best satisfied at low CM angles. At high CM angle the uncertainty on the differential cross section increases and strongly depends on the potential parameters. Consequently the calculation of the spectroscopic factors from the available data would not yield reliable results.

Ground State

The deuterons from the transfer reaction to the ground state can only be selected using one restriction, namely on the energy of the deuterons. Due to the lack of γ rays no d - γ coincidence condition can be imposed. This affects the purity of the selected reaction channel. Contamination from the population of the 694 and 1007 keV states are present since the FWHM of the excitation peak is close to 1 MeV. Only deuterons for which the energy corresponds to a ^{67}Ni excitation energy from -100 keV to 100 keV are taken into account. This interval covers 18.5% of the total excitation peak. This narrow interval

was chosen to suppress the influence of deuterons from transfer reactions to the 694 keV level. The obtained differential cross section in the CM frame is shown in figure 4.18d. In principle one can subtract the deuterons from the 694 keV state from the angular distribution of the ground state. However the statistics of d -694 keV coincidences in the region of the ground state excitation peak are very low. By scaling and subtracting these few counts from the angular distribution of the ground state the uncertainty increases. Therefore this procedure is not used and only an energy gate on the excitation energy is imposed. One can also decrease the influence of the 694 keV state by selecting deuterons for which $-800 < E_{\text{exc}}^i < -500$ keV. However the shape of the obtained angular distribution is similar to the one in figure 4.18d.

DWBA calculations have been performed for ℓ -values from 0 to 4. For ℓ -values 0, 2 and 3 the spin-orbit coupling is the same as for the excited states. For $\ell = 1$ an anti-parallel coupling is assumed corresponding to the $p_{1/2}$ orbital. This is the expected configuration of the tentatively assigned $(1/2^-)$ ground state [Jea05].

4.6 Discussion

4.6.1 ^{67}Ni Ground State

The analysis of the ground state is limited to the detected deuterons, since no γ rays are emitted. Due to the wide energy spread of the particles an accurate identification of the transfer reaction to the ground state is difficult. From the excitation spectrum in figure 4.16 we can only conclude that the ground state is populated in the (t, d) transfer reaction. Due to the non-observation of the isomeric decay and the contamination in the excitation spectrum around 1.8 MeV the exact feeding of the ground state cannot be deduced. Since the differential cross section in this experiment is limited to high CM angles, no clear ℓ -assignment can be made. Moreover the selection of deuterons from a transfer reaction populating the ground state is doubtful since one cannot exclude deuterons from transfer reactions to the 694 keV state.

4.6.2 694 keV State

From the observation of a 694 keV γ ray populating the ground state (see figure 4.8), there must be a 694 keV excited state in ^{67}Ni , this is in agreement with other experiments [Dir13, Wea04]. Furthermore d - γ - γ coincidences indicate this γ ray is in coincidence with the 1513 keV γ ray. Now deuterons in coincidence with the 1513 keV γ ray as well as with the 694 keV γ ray populate excited states around 2.2 MeV. Hence an excited state at 2207 keV is expected. This is in agreement with the proposed level scheme in [Dir13]. The spin and parity of the 694 keV state is tentatively assigned to be a $(5/2^-)$ state corresponding to the $\nu f_{5/2}$ shell model orbital. Again we are limited to high CM angles and cannot assign a certain ℓ -value from the data. Nevertheless the shape of the $\ell = 3$ calculation with anti-parallel coupling with the neutron spin to $J = 5/2$, agrees best with the data.

4.6.3 1724 keV State

The observation of a 1724 keV γ ray populating the ground state, indicates there is a 1724 keV excited state in ^{67}Ni , this state has also been observed in the $^{70}\text{Zn}(^4\text{He}, ^7\text{Be})^{67}\text{Ni}$ reaction [Kea78] and in the $^{66}\text{Ni}(d, p)^{67}\text{Ni}$ reaction [Dir13] but not in the β decay study of ^{67}Co [Wea04] or the $^{70}\text{Zn}(^{14}\text{C}, ^{17}\text{O})^{67}\text{Ni}$ reaction [Gir88]. Furthermore d - γ - γ coincidences show this γ ray is in coincidence with the 483 keV γ ray. Deuterons in coincidence with the 483 keV γ ray as well as with the 1724 keV γ ray correspond to excitation energies in ^{67}Ni around 2.2 MeV. Hence also from this observation an excited state at 2207 keV is expected. From the angular distribution corresponding to the 1724 keV state no ℓ -value can be assigned. The spin and parity of this state is tentatively assigned to be a $(3/2^-)$ state, from the (d, p) reaction [Dir13] an $\ell = 1$ transfer is expected. From the limited range in the CM frame that we are sensitive to, we can say that an $\ell = 1$ transfer reaction corresponding to a $3/2^-$ state is possible. But again $\ell = 0$, $\ell = 2$ and $\ell = 3$ are possible as well.

4.6.4 2207 keV State

The d - γ - γ coincidences mentioned above point to the existence of a state at 2207 keV. In the $^{66}\text{Ni}(d, p)$ reaction a state at 2207 keV is also observed [Dir13]. From the level scheme proposed by [Dir13] this state decays to the isomeric state at 1007 keV by emitting a 1.2 MeV γ ray. This is in agreement with the observation of an intense 1198 keV photopeak in the d - γ spectrum in this work. The d - γ - γ spectrum gated on the intense 1198 keV does not indicate any coincident gamma rays in the Miniball detectors. Unfortunately the decay of this 1007 keV isomer following the 1198 keV γ decay could not be observed in the beamdump detector either due to the low statistics. Again the angular distribution of the 2207 keV state is inconclusive and no spin assignments can be made.

Chapter 5

Conclusion

The goal of this thesis was to investigate the structure of ^{67}Ni via the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ transfer reaction in inverse kinematics. One nucleon transfer reactions, such as these, are known to be good probes of the single-particle character of nuclei. In this perspective, the experiment offers a means to study ^{68}Ni which manifests properties of doubly-magic nuclei. The main motivation of the experiment performed in 2011 at ISOLDE, CERN was to study the $^{66}\text{Ni}(t, p)^{68}\text{Ni}$ reaction. In this reaction one directly obtains information on the internal structure of ^{68}Ni . The $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ reaction is a secondary source of information.

The ^{66}Ni beam is produced at ISOLDE and delivered to the REX-ISOLDE beamline where it is shaped, pulsed and post-accelerated to 2.6 MeV/A. The beam impinges on a thick ($500\text{ }\mu\text{g}/\text{cm}^2$) tritium loaded titanium target. The detection system consist of the T-REX array of silicon strip detectors and the Miniball array of germanium detectors.

The absolute photopeak efficiency of the germanium detectors has been determined via the source activity, the cascade method and the sum-peak method. All methods agree well, the absolute efficiency of a 1 MeV γ ray is almost 6%. The efficiency calibration also showed that the add-back procedure significantly increases the efficiency for high energetic gamma rays.

The data analysis of the experiment includes the reaction channel identification, the construction of d - γ - γ spectra, the excitation spectrum and the angular distribution of deuterons from different reaction channels.

Protons, deuterons and tritons are successfully identified in ΔE - E plots from the telescope configuration of the T-REX detectors. The detection and accurate identification of deuterons is limited to the forward detector only, from 27° to 70° in the lab frame. The deuterons emitted at angles over 70° do not have sufficient energy to pass through the ΔE detector. Consequently they could not be discriminated from the other reaction products.

By means of prompt d - γ coincidence gates the gamma spectrum of the (t, d) reaction, which populates states in ^{67}Ni , was constructed. The Q -value of the $^{66}\text{Ni}(t, d)^{67}\text{Ni}$ is -0.450 MeV and the energy of the relative motion in the CM frame is 7.507 MeV. Populated excited states up to 3.6 MeV are observed. From the analysis of the d - γ - γ coincidence spectra several coincident gamma rays are identified. The observation of the coincidence between the 483 and 1724 keV gammas, and the 694 and 1513 keV gammas suggests there

is an excited state at 2207 keV, this is in agreement with the proposed level scheme from [Dir13]. From the intensity of the observed γ rays the relative feeding of prompt decaying excited states was deduced based on the level scheme from [Dir13]. The feeding of the 1007 keV isomeric state could not be calculated since the isomeric decay is not observed in the beamdump detector. The results show that, when neglecting the ground state and isomer, the $(5/2^+)$ state at 2.2 MeV is most strongly populated, followed by the $(5/2^-)$ state at 694 keV and the $(3/2^-)$ state at 1.7 MeV.

The excitation spectrum of ^{67}Ni is constructed from the energy of the deuterons. The energy resolution of this spectrum is very low, about 1 MeV. This is mainly due to the straggling of the beam in the target but also due to the deuteron straggling in the Mylar foils, the kinematic compression and the finite energy resolution of the detectors. Hence the different reaction channels populating excited states in ^{67}Ni cannot clearly be identified from the deuterons only. One can however observe that the ground state $(1/2^-)$ and isomeric state $(9/2^+)$ are also populated.

The angular distribution of the elastic $^{66}\text{Ni}(t,t)^{66}\text{Ni}$ channel, and the transfer reactions channels populating the ground state, the 694, 1724 and 2207 keV states has been investigated. The angular distributions of elastically scattered tritons was used to calculate the beam intensity by comparison with the calculated differential cross section using Fresco [Tho88] and global OMP's for tritons from Becchetti and Greenlees [BG69] in [PP76]. The beam intensity is $2.5(3) \cdot 10^6$ pps. The angular distribution of deuterons is limited to CM angles between 70° and 120° . The data lie far from the region of the first maximum which occurs at low CM angles. Consequently it is not possible to accurately determine the transferred angular momentum $\ell\hbar$. The calculation of spectroscopic factors, under the assumption of a certain ℓ -transfer, does not yield reliable results either since the approximations made in the DWBA theory are best satisfied at low CM angles. The DWBA calculation were performed using global OMP's from Becchetti and Greenlees for the triton channel and global OMP's from [Hea06] for the deuteron exit channel.

In summary, the results from the data analysis of the $^{66}\text{Ni}(t,d)$ reaction are in agreement with the level scheme proposed by [Dir13]. The gamma rays and d - γ - γ coincidences correspond to observed transitions in the $^{66}\text{Ni}(d,p)^{67}\text{Ni}$ reaction. The excitation spectrum of ^{67}Ni deduced from the deuteron energy has a low resolution, which limits the ability to obtain quantitative information on the population of the excited states. Furthermore DWBA calculations have been performed and compared to the experimental angular distribution of the ground state, the 694, 1724 and 2207 keV states. Due to the limited range in the CM frame the transferred angular momentum value could not be determined, hence no spectroscopic factors could be deduced.

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