Report for the degree of Masters in Physics

Probabilistic Neutron Tracker

Making Good Guesses on Invisible Interactions in Subatomic Physics

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Department of Fundamental Physics
Chalmers University of Technology &
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Abstract

In order to gain further understanding of subatomic physics, research is conducted close to the drip line, where the ratio of the constituents of the nuclear core is at the extreme. In experiments, liberated neutrons, which have no charge, are difficult to detect because only the effects of collisions with charged particles can be observed. Collisions at the subatomic level may involve different physical processes and branch into several other collisions.

A neutron detector called LAND, situated in the GSI facility outside Darmstadt, Germany, is capable of observing these collisions. The algorithm currently used to recognize neutrons from the collisions is heavily based on macroscopic observations of how the neutron detector behaves. It is greedy and therefore tends to underestimate the number of neutrons for complicated events.

This project continues investigations from an earlier project, aimed at designing a probabilistic method to reconstruct neutrons from neutron detector data. Visualisations of the new algorithm show promising results of resolving neutron paths and branching and statistical results show good capabilities in estimating the number of neutrons. Some very important problems could not be solved, but the effects of the problems can be understood and explained from the obtained results.

An algorithm based on probability functions of subatomic interactions seems to be a viable concept and will most probably see continued exploration and improvement by future masters students.

Sammanfattning

För att bättre förstå den subatomära fysiken bedrivs forskning med exotiska atomkärnor där andelen protoner och neutroner är oproportionerlig. Neutroner som frigörs vid dessa experiment är svåra att detektera eftersom de inte har någon laddning och därför inte kan interagera elektriskt. Endast spår av laddade partiklar som neutroner kolliderat med kan observeras. Kollisioner på den subatomära nivån kan innefatta en mängd olika fysikaliska processer och föranleda ytterligare kollisioner, vilket kan göra spår från enstaka neutroner komplexa.

Neutrondetektorn LAND, som är en del av GSIs forskningsanläggning utanför Darmstadt i Tyskland, kan observera dessa kollisioner. Algoritmen som för närvarande används för att återskapa neutroner från spåren i detektorn är till största delen baserad på makroskopiska observatoner av hur neutrondetektorn beter sig. Den är girig och tenderar därför att underskatta antalet neutroner för komplicerade event.

Detta projekt har utgångspunkt i ett tidigare projekt med syftet att utveckla en sannolikhetsbaserad metod för att återskapa neutroner från spåren i detektorn. Visualiseringar av den nya algoritmen visar lovande resultat för att spåra neutroners banor och förgreningar. Statistiska resultat visar att algoritmen är väl kapabel att uppskatta antalet neutroner. Några väsentliga problemställningar har inte kunnat läsas till fullo, men effekterna av problemen kan förstås och förklaras utifrån erhållna resultat.

En sannolikhetsbaserad algoritm har visat sig vara ett gångbart koncept för dessa subatomära reaktioner och kommer sannolikt att utforskas och utvecklas vidare av framtida examensarbetare.

Contents

Chapter 1

Introduction

Subatomic physics was born in 1896 when Henri Becquerel discovered radioactivity. One century of research in the field has resulted in many interesting discoveries and today, a fundamental theory for the basic physical interactions in the universe has been established. This theory, called the standard model, states that we have four and only four fundamental forces in the universe; the strong force, the weak force, the electromagnetic force and gravity. The strong force holds the smallest known particles together, the weak force is responsible for beta decay, the electromagnetic force explains why electrically charged particles are attracted or repelled, and gravity pulls matter together.

By exploring exotic nuclei on the drip line, where the number of neutrons is unusual and disproportional to the number of protons, we can gain knowledge of the characteristics of the strong force. There are still many fundamental questions to be answered, research in this field would not only benefit applied physics.

Exotic nuclei are not just lying around waiting for a physicist to start working on them. Since they have short lifetimes, they need to be observed immediately after having been created. This is done at tremendous particle accelerator complexes around the world. The basic procedure is to accelerate a beam of heavy nuclei and smash it into a target, which results in an output of various new nuclei. These different nuclei are then separated from each other by their mass to charge ratio, resulting in beams of practically any desired type of nucleus.

To construct experiments suitable for the exotic nuclei, you need to know what you are looking for. The usual procedure here is that a theoretical physicist comes up with a theory that needs to be rejected or approved by an experimental physicist. One such theory is the halo nuclei, a nuclei where some of the nucleons form a very loosely bound shell structure around the remaining core nucleons as depicted in Figure 1.1. Some nuclei of this kind mimic the borromean rings in Figure 1.2 - if you remove one part of the bound system, the whole system would fall apart. Simply by creating nuclei expected to have this halo feature, breaking them up and analysing the constituents, we can see if the theory holds or not. Another example of what we may want to see in experiments is the much debated tetra neutron. There are theories suggesting that four neutrons can form a stable cluster. Even if the idea of four bound neutrons is not generally theoretically expected, it needs to be investigated.

One particular place where these kinds of experiments are carried out is the

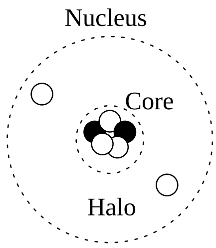

Figure 1.1: Halo shell structure, halo radius exaggerated. A few neutrons are very loosely bound to the core compared to the other nucleons.

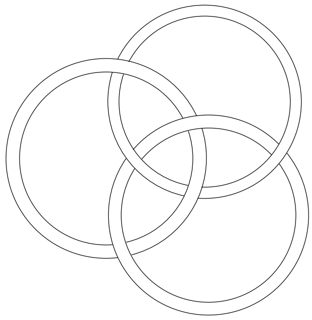

Figure 1.2: The Borromean rings; if one ring is removed, the other are no longer bound.

GSI research centre outside Darmstadt, Germany. The GSI complex houses equipment and machinery required to perform high energy nuclear physics experiments. A part of GSI is the ALADiN-LAND setup, which includes the dipole magnet ALADiN, several ion detectors and a multi neutron detector called LAND. It is constructed for beams of exotic nuclei with energies from approximately 100 MeV/u up to more than 1 GeV/u, which is equivalent to speeds up to 90 percent of the speed of light.

Charged particles easily interact with other charged particles, even at significant distances. Electronics is based on the principle of charge and so detecting charged particles in an experimental setup is not a difficult concept. Neutrons are much more problematic since they have no charge, so an interaction mediated by the strong force involving and liberating charged particles is required. The task of this thesis is to come up with a probabilistic way of transforming the detection of these interactions back to neutrons.

The best way to develop such an algorithm is to study how the detector behaves when the number of neutrons is known. By looking at the break up of deuterons, a nucleus consisting of only a proton and a neutron, we limit the possible number of neutrons in the neutron detector to one. An experiment with deuterons was performed in 1992 at GSI. Since then, the whole ALADiN-LAND setup has been moved from one cave to another, and some documentation has also been lost. By digging through corrupt databases, hunting down decomposed setup schematics, decoding German logbooks, eyeballing old photographs and interrogating past experiment crew members, we have been able to recreate the most important aspects of the experimental setup. This gives access not only to the deuteron experiment data, but also to experiments with other exotic nuclei.

Chapter 2

Theory

2.1 Prerequisites

The theory required for this masters project involves kinematics with neutrons and protons with kinetic energies from tens of to a thousand of MeV/u. Classical kinematics will not work in the higher energy domains, so all physics must conform to the theory of special relativity.

A neutron travels unaffected through media unless a hard collision occurs, but a proton is slowed down due to its charge as explained by the Bethe formula. The deceleration of charged particles in the media in this project, especially in sheets of iron, is significant and therefore we will only consider neutrons as freely travelling particles.

2.2 Neutron detection

Detecting any particle is a matter of finding traces that are left as they travel through a detector. Certain materials, called scintillators, produce photons when charged particles travel through them. The photons can in turn be measured using PM tubes whose signals are recorded with sensitive electronics.

Neutrons pose a big detection problem since they have no charge and thus appear invisible to detectors. The only trustworthy way neutrons can interact with other matter and leave traces, is via hard collisions with protons or other nuclei liberating charged particles, which can be detected. A collision can also produce a shower of outgoing particles, including more invisible neutrons. Neutron detection is therefore a second order observation. By analysing the hits and tracks of the charged particles, neutrons that entered the detector can be reconstructed.

2.3 Scattering cross section

A scattering cross section is a measure of how likely it is for a collision to occur with a given projectile and target. For example, elements of moderately heavy nuclei like iron have a higher scattering cross section with incoming neutrons than elements with lighter nuclei like carbon. Scattering cross sections are generally energy dependent, but for the materials and energy ranges of the LAND experiment, they are practically constant [9].

2.4 Bethe formula

Charged particles slow down when travelling in matter, due to for example Coulomb interaction. The Bethe formula[1] is a solution to the second order quantum perturbation describing the retardation as dE/dx. The stopping power is roughly inversely proportional to the kinetic energy except for very small energies and this rapid deceleration when particles are close to stopping is called a Bragg peak.

2.5 Quasi free scattering

Interaction at subatomic levels, for example scattering processes, is very complex to model in detail and must be approximated with relatively coarse models. In scattering collisions with neutrons or protons of high kinetic energy, it has been shown experimentally that the structures of nuclei become virtually transparent. A nuclei can then be treated as a loose group of separate nucleons with very simple kinematics. This simplified model of scattering is called quasi free scattering. Since the experiments which will make use of the neutron tracking algorithm developed in this project are in the energy range of several hundred MeV, we expect to mostly see quasi free scattering of the neutrons in the detector.

2.6 Special relativity

As has been mentioned, the kinetic energies involved in the experiments related to this project require relativistic consideration. The mass, momentum and kinetic energy of an object in motion are:

$$\begin{aligned} m &= \gamma m_0, \\ p &= \gamma m_0 v, \\ T &= (\gamma - 1) m_0 c^2, \text{ with} \\ \gamma &= \left(1 - \frac{v^2}{c^2}\right)^{-1/2}, \end{aligned}$$

where $m_0/c^2 = 940$ MeV/c^2 is the rest mass of a neutron, and γ is the Lorentz factor. The expression for the kinetic energy is easily twisted and turned to find the speed of a high energy neutron:

$$v/c = \sqrt{1 - \left(\frac{T}{m_0 c^2} + 1\right)^{-2}}.$$

[1]Often referred to as the Bethe Bloch formula, which is an approximation of the mean field potential with a constant.

Chapter 3

Experiment

3.1 Experimental setup

The development of the probabilistic neutron tracking algorithm is based on analysis of data collected from experiments at GSI. The experimental setup consists of an ion production facility and the accelerator SIS which can accelerate ions to kinetic energies up to about 90 percent of the speed of light, a target in which the projectile particles interact, a magnet to separate particles of different mass and electric charge coming from the target, and a set of detectors. A rough sketch of a typical setup can be seen in Figure 3.1 and a hand drawn schematic of the experimental setup from 1992 used in this project is shown in Figure A.2 in Appendix A.

It should be noted that this section will describe the setup used during the deuteron experiment in 1992, but other experiments performed at the same setup are not fundamentally different. What differs is usually positions of small detectors, detector parameters and the additions of new detector types over the years that do not heavily alter the neutron data. Our algorithm should be able to work in all setups that can provide three dimensional position information and time from neutron interactions.

LAND is the largest detector in the setup and is used to detect neutrons. It consists of 200 paddles made of plastic scintillator material and iron. Each paddle has a sandwich structure of 10 layers of scintillating plastic for neutron detection and 11 layers of iron acting as neutron converters. The short ends are connected to PM tubes which convert photons from the scintillator material to electrical signals. A cut of a paddle is shown in Figure 3.2. The paddles are arranged in 10 layers with 20 paddles in each layer. Each layer has been rotated by 90 degrees with respect to the immediate neighboring layers, creating a crossed structure as shown in Figure 3.3.

In front of LAND is a detector called the VETO wall which in 1992 consisted of two crossed layers of scintillator material, but has since been rebuilt to have only one layer. The VETO wall is used to detect any spurious charged particles that could sneak into LAND together with neutrons. Therefore it consists only of 1 cm thick sheets of scintillating plastic and no iron to moderate particles.

Another similar detector is the TOF wall which detects ions after the target that are bent from a straight flight path by the ALADiN magnet. This detector

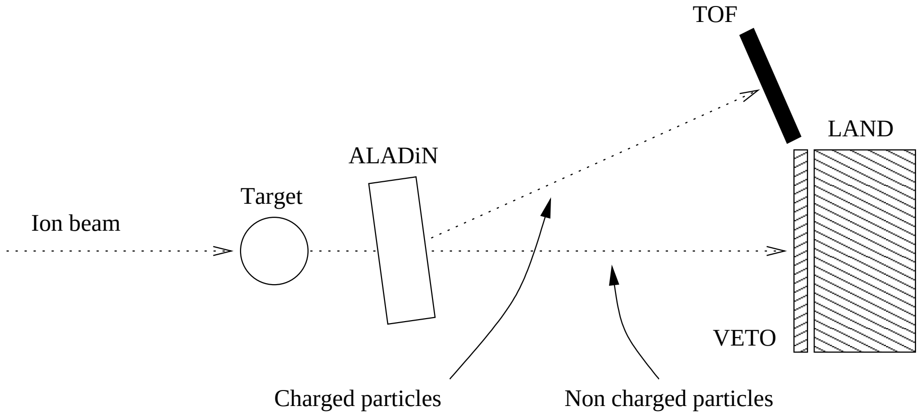

Figure 3.1: Rough sketch of the ALADiN-LAND experimental setup at GSI. An ion beam collides with a target which produces parts of nuclear cores, particles and radiation. The ALADiN magnet changes the direction of charged particles to be detected in the TOF detector, other particles continue straight forward into the VETO and LAND detectors.

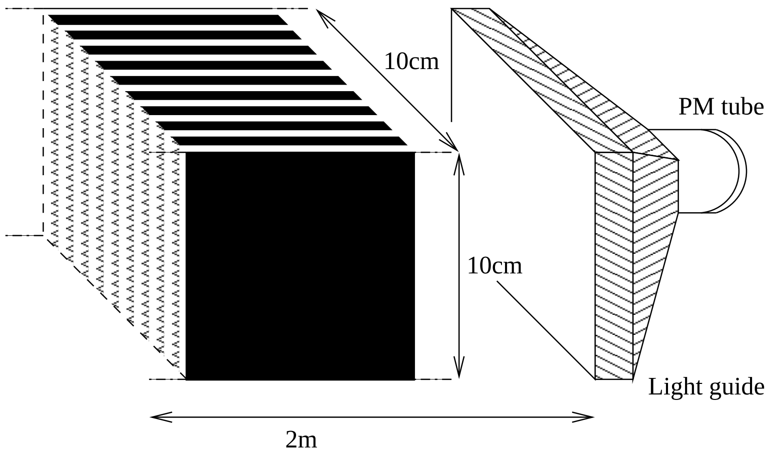

Figure 3.2: Sketch of a part of a paddle in LAND. The dark volumes are made of iron, the bright volumes are made of scintillating plastic. To the right is a light guide to a PM tube that amplifies photon currents created from charged particles travelling through the scintillating plastic in the paddle.

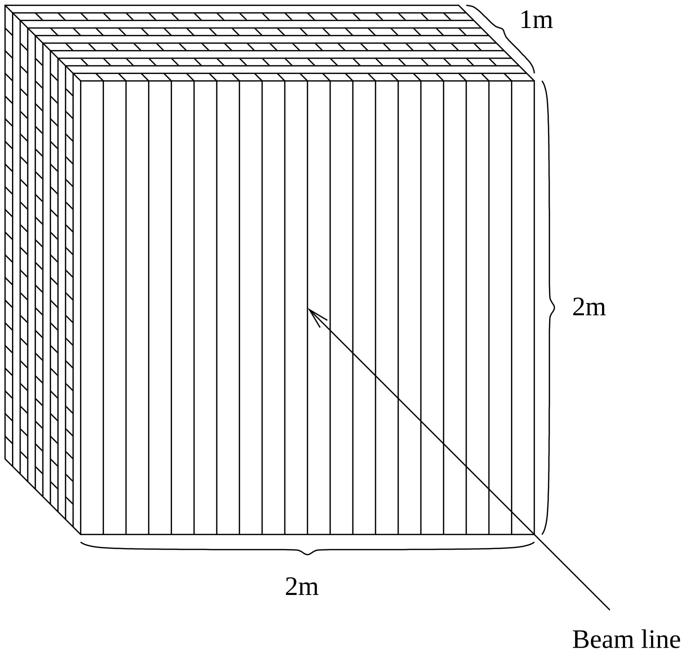

Figure 3.3: Sketch of the LAND structure with crossed paddle organisation.

consists of one layer of scintillator material.

The remaining detectors are smaller and used along the flight path to find time, position and charge for ions and scattered particles. One such detector used to find time and charge is the POS detector, which consists of a small sheet of scintillator material and four PM tubes, see Figure 3.4. Another type of detector worth mentioning is the Stelzer detector which also delivers decent position information, see Figure 3.5. To classify events in the experiment, certain combinations of detector signals, called triggers, are assigned and recorded as base two bit patterns. Collections of such bits are called trigger patterns. These can be used to isolate interesting events from spurious or in other ways unwanted events, for example when outgoing particles from the target are deflected too much or the event was recorded due to a cosmic muon passing through the detector. Further details on trigger patterns can be found in Appendix A.

In the deuteron experiment from 1992, code named S107, deuterons were shot against lead and carbon targets [1]. Close inspection of recorded parameters for S107 and data collected from the experiment gave a slightly different layout to the logbook which we present in Figure 3.6. The logbook is presented in detail in appendix A Positions given in the logbook are possibly off by a few centimetres due to faulty laser measurements [10]. However, with no other information accessible, we settled with those values.

3.2 LAND data

In order to understand certain restrictions and limitations in the development of our algorithm, this section will explain how data from LAND is used to

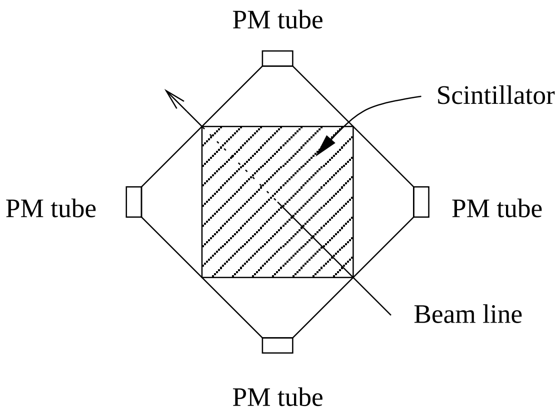

Figure 3.4: Sketch of a POS detector used to find time, position and charge of particles along the beam line. Placement at different angles after ALADiN will give the mass to charge ratio of the detected particles. The sheet of scintillating plastic is connected to four PM tubes that record the photons emitted as a charged particle passes through the scintillator.

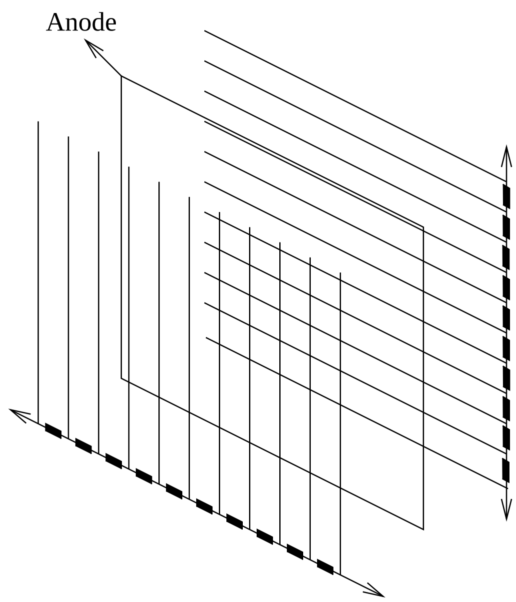

Figure 3.5: Sketch of a Stelzer detector. The coordinates of a hit in such a detector is determined from the delay line time.

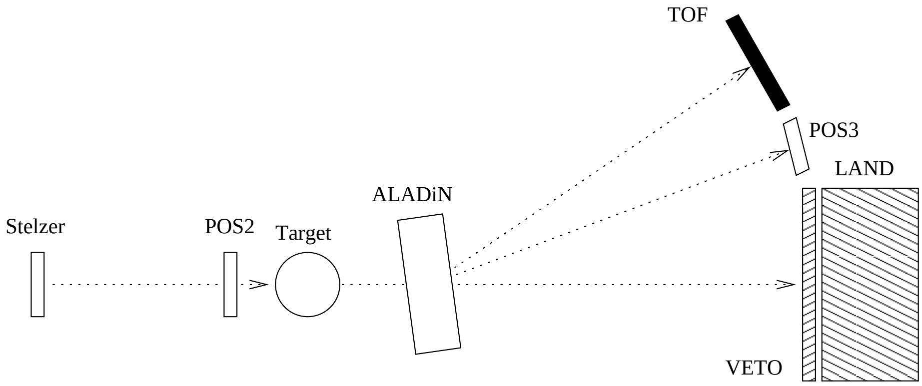

Figure 3.6: Real setup for the S107 experiment as deduced from experiment database and detector data. The TOF wall is set to detect protons, LAND to detect neutrons and POS3 to detect deuterons that do not split up in the target. The Stelzer detector is used to focus the beam and together with POS2 it sets a time reference for all hits in the setup.

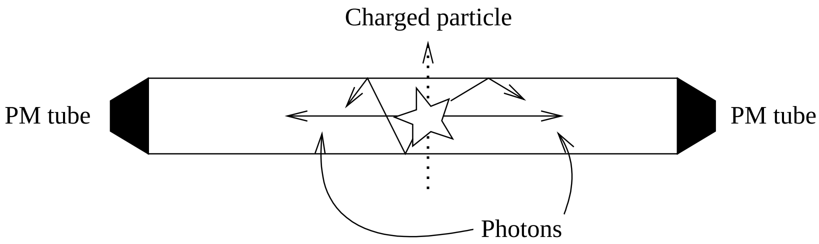

Figure 3.7: Basic features of a LAND paddle. When a charged particle passes through the scintillating material, photons are emitted and recorded by the two PM tubes. Comparison of the time of the signals from the PM tubes gives a time stamp and a coordinate along the paddle for the charged particle.

reconstruct human readable information.

When a charged particle crosses a plastic scintillator, photons are emitted and travel inside the scintillator. The paddles in LAND are equipped with PM tubes that measure the photons, as illustrated in Figure 3.7. By recording the time when the two PM tubes for a paddle detect the photons, the charged particle can be assigned a time stamp and a coordinate along the paddle:

$$\begin{aligned} T &= \frac{t_1 + t_2}{2}, \\ P &= v\frac{t_1 - t_2}{2}. \end{aligned}$$

P gives either the x or y coordinate, depending on in which layer of LAND the paddle is located. See [7] for more details and for the not so difficult derivation of the above equations.

This takes care of the lengthwise coordinate and the other two are simply determined by the location of a paddle inside LAND. For example, the 20 paddles in the first layer of LAND all report the same z coordinate. The lengthwise coordinate has an estimated error of about ± 5.2 cm [2], and since the LAND paddles have widths of 10 cm, LAND can be visualised roughly as a box with cubes of $10 \times 10 \times 10$ cm^3 granularity.

3.3 Processing of experimental data

In order to be able to work with data from the experimental setup, detectors must be mapped to the streams of collected data. In 1992, cable mapping for detectors and electronics were stored in binary files in the RZ format provided by the ZEBRA/PAW software packages. The RZ file for S107 was probably damaged and could not be read by the extraction program used to read such files for other experiments, so the file had to be processed manually using hex dumps. Interesting parts of the file were cut out by hand and injected to a modified version of the extraction program, which produced the required data for the detector mapping. Corrupt binary files are not completely trustworthy, but the extracted data passed the extraction error checking. The mapping for LAND with all its PM tubes was exactly the same as other experiments with just a few differences that were resolved by hand, which is another indication that the extracted data is probably correct.

A program called *unpacker* [11] was used to see raw data from events. The program can print information like signals from detectors. This was especially useful for checking and confirming the cable mapping of LAND extracted from the RZ file. The program could further be used to see the cable mapping of all other detectors in the setup. The different types of detectors used in S107 had different number of cables attached and thus we could determine what detectors were enabled. Some knowledge and imagination about what kind of output the detectors would give in various places in the setup also helped. Coupled with the manual extraction of the RZ file, this gave us the experimental setup shown in Figure 3.6.

To convert raw detector data to usable hit data in detectors, we used *land02*. This program can produce data in a number of formats, most importantly three dimensional positions for hits inside LAND. Currently, the program also implements the so called *shower algorithm* to estimate the number and parameters of neutrons that enter LAND [3][5]. The algorithm practically tries to assign hits within volumes and physical laws to as few neutrons as possible which can lead to underestimating the number of neutrons. For experiments where the number of neutrons is crucial information, this algorithm should not be relied upon.

The last, and possibly in our case among the least, important part in the analysis consisted of drawing histograms and correlation plots in ROOT, a large analysis software package developed at CERN. This software package is very similar to software such as MATLAB, but was conceived to be able to analyze large data sets from particle physics experiments. Even though it is a very capable and flexible analysis tool, it was used only to look at statistics of detector data to find global features in events early in the project.

Chapter 4

A probabilistic neutron tracker

4.1 Background

The first attempt to recreate neutrons from hits in LAND is described in [3]. It was a primitive shower recognition algorithm based on simulated data, excluding hits originating from photons and other charged particles and combining the remaining hits to neutrons. This approach is known to be greedy and the number of neutrons is often underestimated. Alongside construction and testing of LAND, an analysis program was developed in FORTRAN 77 [4]. The program included an improved version of the shower recognition algorithm, still developed from simulated data but tested on real physical events with decent results [5].

To further improve the algorithm and evaluate systematic errors, the S107 deuteron experiment was performed. Deuterons are guaranteed to generate events with only one neutron which simplifies the characterisation of the neutron detection in LAND. This was the basis for the next step in the evolution of the algorithm. In a master's thesis from 1997, a more sophisticated version of the shower algorithm is presented [6].

Beginning in 2003 the whole LAND analysis program was rewritten into C/C++ code, resulting in *land02* [7]. The program employs the shower algorithm from the FORTRAN era.

The first attempt to construct a probabilistic neutron tracker was made in fall 2008 [8]. Due to compatibility problems with the 17 year old S107 data and *land02*, and due to insufficient documentation, only a limited, preprocessed version of the S107 data was available. Discovery of far too many events breaking causality in the S107 data lead to unexpected investigation detours and creation of the first probabilistic neutron tracking algorithm was postponed.

4.2 Overview

The new algorithm is designed to avoid the previous underestimation of neutrons. Hits are connected in every possible way, evaluated for likelihood and compared to find the most probable scenarios and thereby how the neutrons travelled from the target. During the development and debugging, the complete kinematics is visualised for further analysis. Since LAND was designed to resolve multiple hits up to about six [2], the algorithm has been optimized for one to six neutron events, where quality is inversely proportional to quantity.

The input to the new algorithm is the hit data that *land02* produces, which then runs through the three parts of the algorithm; *part A* which is a preprocessor that filters the data to get clean physical events, *part B* that uses probability functions to find the most probable scenario for an event, and *part C* where the results are presented and visualised.

4.3 Part A - the preprocessor

The large amount of hit data from *land02* requires some preprocessing before it can be fully analyzed. Not all events are relevant for analysis, so the first step is to filter out events of no interest by their trigger patterns, leaving only good physical events.

The next step is to clean up the hit data for the good events. Since there is no use for hits lacking position or time information, hits with a NaN value in x, y, z or t are removed. The procedure of determining the coordinate along a paddle described in Section 3.2 can sometimes lead to hits outside LAND. Since these hits hold false information they are removed, but at the same time counted for bookkeeping reasons.

The trigger pattern requirement of good beam should generate events with a valid T0[1]. Some events still lack this, making their time information useless, so they are assigned artificial T0s from the mean of the prior events. This is possible since S107 uses monoenergetic beams, and the master start trigger time is stable. The artificial T0s need to be distinguished from the real ones, so events lacking a time reference are flagged.

A typical LAND experiment is in the energy range 100 MeV/u to 1 GeV/u, which allows us to put upper and a lower limits on the energies of the incoming particles. Since free neutrons all have the same mass, the energy limits are equivalent to limits on the velocity, which in turn, due to the static distance between the target and LAND, are equivalent to limits on the time of flight. Hits outside these limits are removed since they can not have originated from a neutron of interest.

Since the position resolution of a hit is restricted by the geometry of the paddles, the discrete coordinates are randomised within the paddles by land02 to avoid artifacts in the analysis. This random fraction has no physical meaning and is hence removed by the preprocessor, moving the two discrete coordinates to the middle of the paddle. The third coordinate, the one along the paddle, is continuous and it is therefore left intact.

Particles with high momentum can penetrate multiple paddles, leaving a trail of hits in LAND. Hits that lie inside a (dx, dy, dz, dt) volume of (10.4 cm, 10.4 cm, 11.1 cm, 1 ns) are combined and reduced to one hit. The resulting hit has the coordinates and time of the first of the combined hits. The original number of hits in each event is saved for later use.

The hits of each event are then sorted in time, which concludes the preprocessing part of the algorithm.

[1] A time reference offset in land02.

4.4 Part B - the probability calculator

The second part of the algorithm generates the most probable complete kinematic scenarios for the now preprocessed data. This is done by applying four different probability functions to the tracks of the different scenarios; the neutron path length, the hit multiplicity, the scattering angle, and the momentum distribution.

In order to test the algorithm on events with multiple neutrons, events from the S107 experiment are merged to create larger events with desired number of neutrons. One detail that was overlooked in the merge was that there can be only one hit per paddle. If two events have a hit each in the same paddle, the latter hit should be discarded.

4.4.1 Path tracking

Finding the most probable neutron tracks naïvely requires an exhaustive search. Probabilities between hits and the set of incoming neutrons can be accumulated multiplicatively for an estimate of the total probability for a scenario. This works up to a little above 10 hits, but the rapid growth of the number of possibilities becomes unmanageable after that. In a very bad case scenario, we may have 6 neutrons, each spawning 5 hits giving a total of 30 hits. A lower estimate on the number of combinations ($29! \approx 8.8 \cdot 10^{30}$, not taking violated physical laws into account which have to be evaluated on the fly) puts even the number of states of a Rubik's cube ($4.3 \cdot 10^{19}$) to shame.

As long as the number of hits in an event is relatively low, a simple preorder search, explained in Appendix C, with probability pruning can be utilised. The run time for the preorder search grows remarkably between 12 and 13 hits. Above that, the search was approximated. Since this is largely a combinatorial problem, a slightly modified variant of the *ant colony optimization* algorithm was chosen. The classical algorithm is explained in detail in Appendix D. An overview of how ACO was applied in this project follows:

- One event can be explained by many scenarios, where each scenario consists of a number of neutrons, the hits that they create in LAND and a total probability estimate. The ACO as implemented in our algorithm gets the hits of an event as input and looks for scenarios by generating paths for between one and six neutrons.

- For one neutron, the ACO creates 50 single ants which start in the target. Each ant will visit all hits in the later steps of the algorithm. For two neutrons, the ACO creates 50 pairs of ants, each pair starting in the target. The pair of ants will together visit all hits only once. It works similarly for up to six neutrons.

- When one ant, or a small group of ants if the algorithm looks for scenarios with more than one neutron, has visited all hits, the probability functions are evaluated and accumulated. The resulting probability value is compared to a list of scenarios. If it is better than the worst scenario in the list, it is saved and the bad scenario is discarded.

- The pheromones from the ACO is stored on virtual paths between the target and the hits, including between the hits. The pheromones are saved and shared between all 50 groups of ants for a set number of neutrons. Every time the number of neutrons changes, the pheromones are removed.

- In classical ACO, ants choose the path to walk by themselves. In scenarios with more than one neutron where many ants share the LAND hits, this would introduce bias in the path lengths. Choosing ants at random to build paths will push path lengths to a common average. Another problem with the classical approach is that an ant only walks straight forward on a simple path without branching. In this project, the hits in LAND may branch which must be taken into account. Both problems were solved by linking hits that have not yet been visited to the hit with the highest probability. The choice of the hit is stochastic exactly as in the classical ACO. Each hit linked this way is assigned a marker telling which ant it belongs to.

4.4.2 Neutron path length

Knowing the neutron scattering cross sections of the iron and scintillating plastic in LAND, it is possible to make a simple but accurate estimate of how probable it is that a neutron of a specific energy travels a certain distance in LAND without interacting. The calculations, which are carried out in Appendix B, give rise to the exponential probability distribution displayed in Figure 4.1. Note that the figure depicts the probability that a neutron has travelled *at least* some distance, not *exactly* some distance, which is why the total area is not normalised.

4.4.3 Hit multiplicity

This analysis has in fact been carried out numerous times already [1][6][8]. All report slightly different results, so we performed the analysis once more to get results consistent with the data processing techniques used in this project.

Hit multiplicity is an empirical measure of the distribution of the number of hits in LAND for each event at some projectile energy. Since the kinetic energy of neutrons impinging on LAND becomes practically continuous after collisions in the target, the histogram needs to be two dimensional as shown in Figure 4.2. The dependence on the number of hits has a strong resemblance to the Poisson probability distribution and the dependence on the kinetic energy is simply a proportional expression for the parameter μ in the Poisson distribution.

Hit multiplicity may seem like an ideal choice for assigning an initial probability to an event. Unfortunately, the kinetic energies of the incoming neutrons must be known which requires a scenario with the neutrons solved. This probability function is therefore applied only when full scenarios are known.

4.4.4 Scattering angle distribution

The distribution of relative hit positions can be neatly characterised with an angular distribution. Calculating the angular distribution of hits requires, for each hit, a vector describing the direction of the incoming particle and a vector describing the direction of the outgoing particle or particles.

This distribution is in theory very useful, but has a number of important practical problems. For example, it turns out to be heavily implicit. There

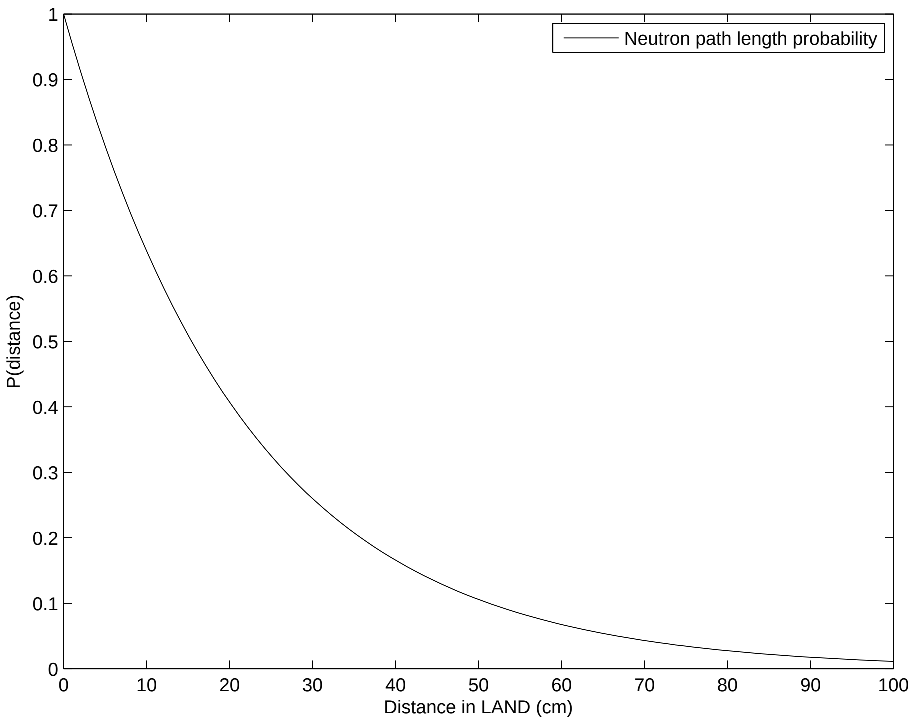

Figure 4.1: Neutron path length probability, derivation in Appendix B. The cumulative distribution is not normalised, because the graph depicts the probability that a neutron has travelled a given distance in LAND without interacting.

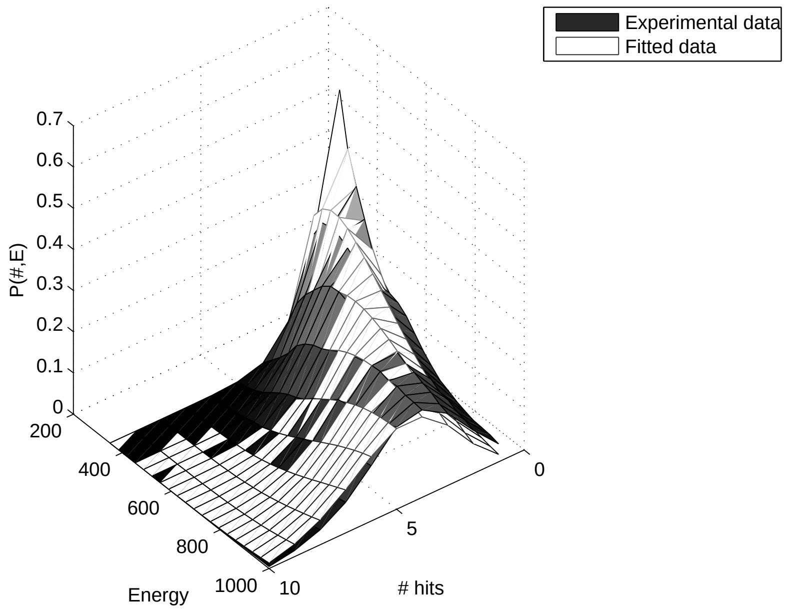

Figure 4.2: Multiplicity distribution surface, based on the energy of incoming neutrons and the number of hits that a neutron causes in LAND. The white superimposed fitted surface is a collection of 2d Poisson distributions, one distribution per chosen energy level.

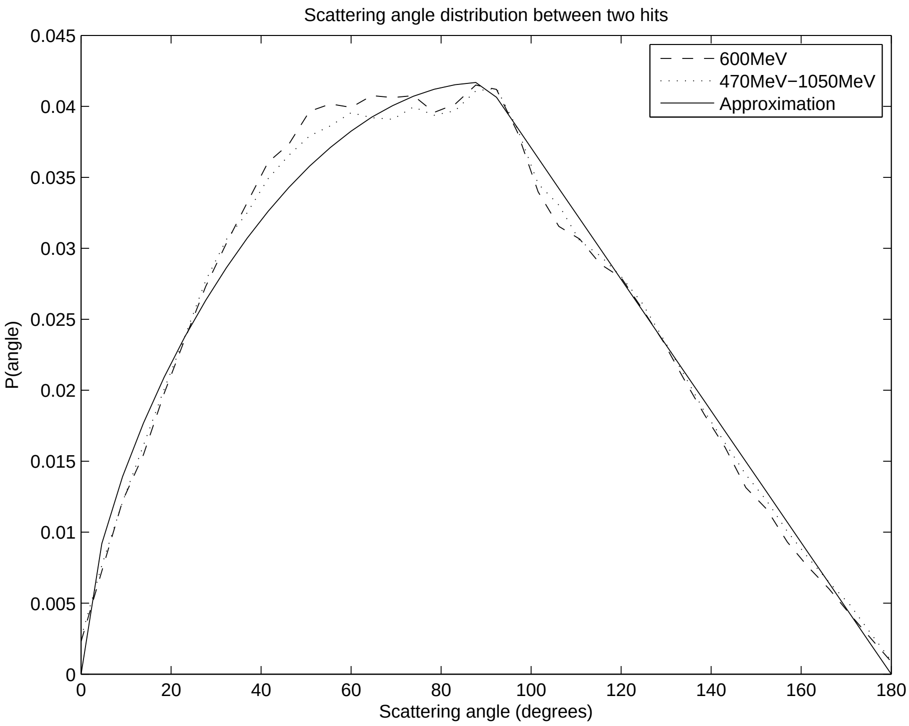

Figure 4.3: Angular distribution from deuterons with the constant kinetic energy 600 MeV/u, deuterons with kinetic energies varying from 470 MeV/u to 1050 MeV/u and the approximated distribution. The approximated distribution is exactly the hard sphere potential scattering cross section, which is a sine curve, under 90° and a straight line above that.

is no prior knowledge about how the hits are related to calculate the angular distribution, and for this project, this distribution is supposed to be used to obtain this knowledge. It is possible to obtain a rough estimate, since the first hits give reliable vectors as long as we know that there is only one incoming neutron. The incoming vector would then be the vector between the target and the first hit, the second vector would be between the first and the second hit. A downside with this solution is that it will not provide any information about the angular distribution of multiple outgoing particles from one interaction. The tracker currently assumes that the distribution is the same for branching first hits.

Another important problem is the rather poor position resolution in LAND. For example, with two hits in adjacent LAND cubes, the angle may vary from 0° to 180°, shown in Figure 4.4. The final algorithm uses this distribution for each neutron and its immediate secondary hits.

4.4.5 Momentum distribution

The energy loss that particles suffers in interactions can be characterised and assigned a probability. Looking at one neutron data with only two hits, the

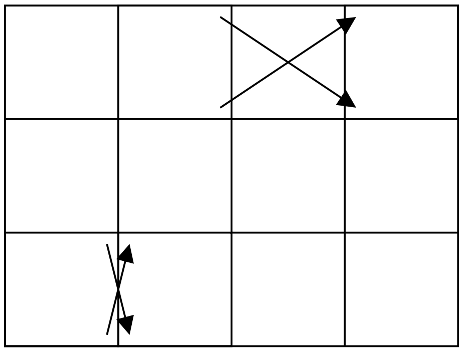

Figure 4.4: Sketch over the scattering angle resolution in LAND. In the worst case, we can have hits in neighboring paddles, resulting in angles from 0° to 180°. The preprocessor however combines adjacent hits so the real worst case is from 45° to 135°.

incoming and outgoing momentum of the first interaction is known by the time of flight method. This distribution is due to the poor resolution of LAND only used for the incoming neutrons and their direct child hits. The distribution is presented in Figure 4.5.

4.4.6 Combining the probabilities

The probability functions do not give absolute probabilities and should only be considered as measurements of how likely the different scenarios are. To get the correct relation between these functions, they are assigned different weights. These weights are applied as powers; the larger the weight, the more significant the probability function. The weights were carefully chosen by trial and error. A set of weights was fed to computers, applying them on data where the result is known and returning the combination of weights that reproduces the result best.

For comparison between different scenarios, we require them to use equal number of probability functions. For example, an event with three hits holds scenarios of one to three neutrons. In the scenario where one neutron caused the three hits subsequently, we have three calls to the neutron path length, one to the hit multiplicity, one to the angle and one to the momentum distribution probability function, resulting in a total of six function calls. In the scenario where one neutron would make a first hit and then scatter to the remaining two in a Y-pattern, we have three calls to the neutron path length, one to the hit multiplicity, two to the angle and two to the momentum probability function, which equals eight calls.

To keep these scenarios on an even footing, we take the geometrical mean of each function, resulting in only four function calls for each scenario. For the case where a function get no calls, it returns its maximum value, keeping the number of function calls intact. The final probability of a scenario is given by

$$P = \prod_{i=1}^{n_{pth}} P_{pth,i}^{w_{pth}/n_{pth}} \times \prod_{i=1}^{n_{mul}} P_{mul,i}^{w_{mul}/n_{mul}} \times \prod_{i=1}^{n_{ang}} P_{ang,i}^{w_{ang}/n_{ang}} \times \prod_{i=1}^{n_{mom}} P_{mom,i}^{w_{mom}/n_{mom}}$$

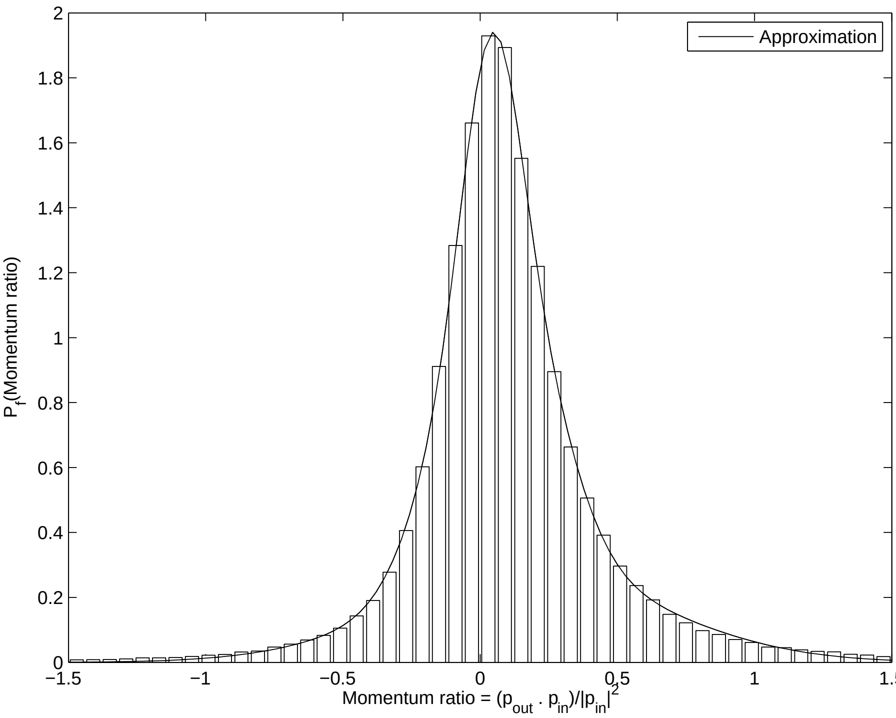

Figure 4.5: Continuous momentum distribution parallel to the axis of the incoming neutron. The approximation is a linear combination of three different Gauss curves and the total combination goes to zero outside the graph extents on the x axis.

where w is the weight and n is the number of times a function is applied. Since every hit has to come from somewhere, n_{pth} will equal the number of hits in the event.

4.5 Part C - the viewer

For swift and easy browsing and visualisation of events and eventually the results of our tracking algorithm, a custom C program using the X11 library was written and extended during the course of the project. The GUI toolkit in ROOT was too contrived and prone to crashing and was therefore quickly dismissed as an option. The first prototype of the viewer in C was completed within a few hours.

Events are loaded from after *part B* of the algorithm. At this stage, the data files contain not only detector data, but also scenarios that link hits in LAND into full neutron paths.

This program was an invaluable tool to come up with new ideas and to improve and find bugs in our tracking algorithm. It also works very well for presenting results.

Chapter 5

Results

Deuteron runs only produce single neutrons, but events with more neutrons can be constructed by merging a number of deuteron events. This trick is visualised by our viewer program in Figure 5.1 to 5.4, together with complete scenarios. Merged events were built by grouping a number of neighbour events in a deuteron run. Hits occurring in one paddle are not filtered, although in a real multineutron experiment, only the first hit in one paddle would be recorded.

Table 5.1 shows the number of neutrons that our probabilistic neutron tracker calculates from events with known number of neutrons. Experimental data was taken from the 600MeV run named 0255. The columns represent the number of real neutrons that travelled into LAND, the rows represent the number of estimated neutrons. The probability values are normalized for each column, meaning the results from the algorithm were normalized on events with a known number of neutrons. Only the most probably scenario for every event is recorded in the table.

Table 5.2 shows the results from the shower algorithm from 1997 based on simulated data [6]. Table 5.3 shows how well the algorithm currently implemented in *land02* performs on the same experiment that our algorithm was tried on with some additional energies. Note that the two shower algorithms are not the same, albeit similar.

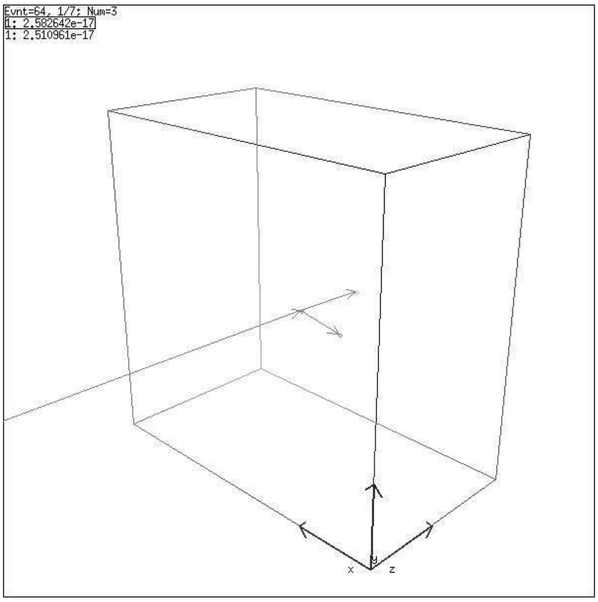

Figure 5.1: One event from a 600 MeV deuteron run. Two scenarios were found as listed in the upper left corner of the figure, only the most probable shown.

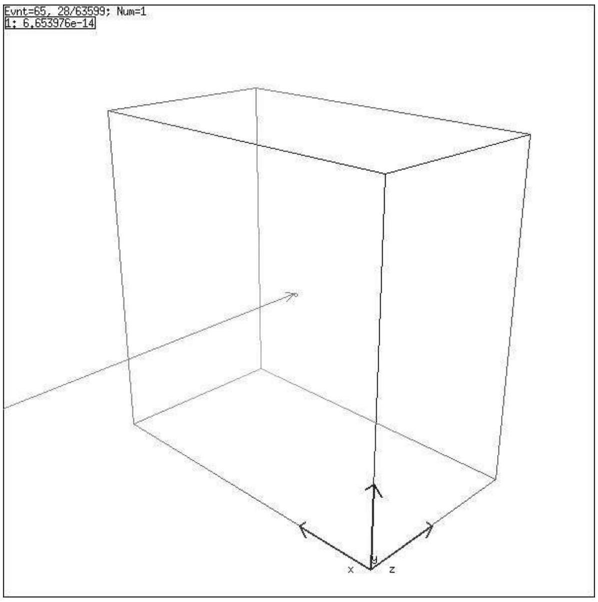

Figure 5.2: Another event from the same 600 MeV deuteron run. With only one hit, there is obviously only one scenario.

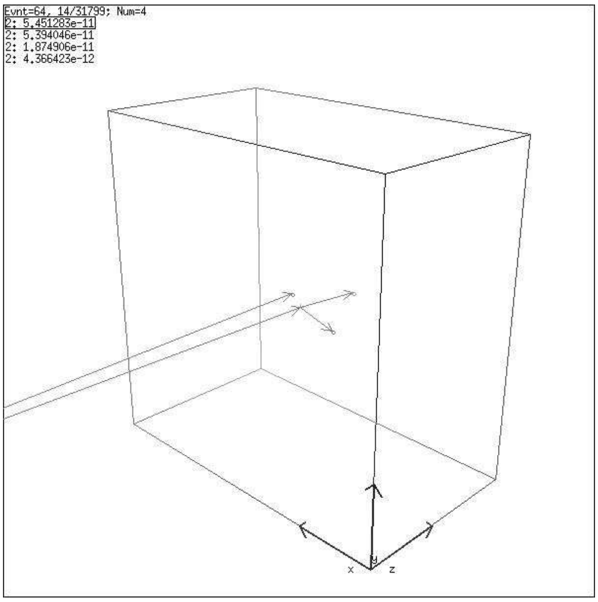

Figure 5.3: Events from Figure 5.1 and 5.2 merged into one to simulate a multiple neutron event. Notice that our algorithm chooses the best scenarios for the individual neutrons in this event.

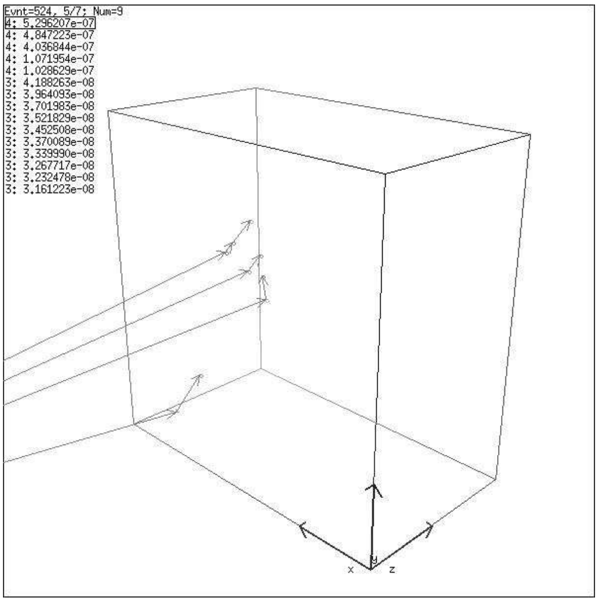

Figure 5.4: Four events from a 600 MeV deuteron run merged into one event to simulate four neutrons. Fifteen likely scenarios were found.

Est. \ Real	1	2	3	4	5	6
1	**0.4775**	0.2403	0.1142	0.0546	0.0396	0.0421
2	0.3511	**0.3011**	0.2016	0.1204	0.0735	0.0575
3	0.1376	0.2396	**0.2354**	0.1883	0.1404	0.1036
4	0.0295	0.1383	0.2027	**0.2080**	0.1829	0.1449
5	0.0039	0.0579	0.1359	0.1885	**0.1951**	0.1836
6	0.0004	0.0178	0.0725	0.1309	0.1658	**0.1780**
7	0.0000	0.0040	0.0274	0.0669	0.1053	0.1306
8	0.0000	0.0008	0.0079	0.0284	0.0573	0.0792
9	0.0000	0.0001	0.0021	0.0091	0.0224	0.0378
10	0.0000	0.0000	0.0002	0.0030	0.0099	0.0204
11	0.0000	0.0000	0.0001	0.0014	0.0040	0.0130
12	0.0000	0.0000	0.0001	0.0005	0.0037	0.0091

Table 5.1: Statistics of the number of neutrons as determined by our probabilistic algorithm on real LAND experiment data, run 0255 at 600MeV. The bold values mark the entries which should be the largest, the algorithm misses just slightly in events with six neutrons.

Est. \ Real	1	2	3	4	5
1	**0.8300**	0.4065	0.2060	0.0690	0.0270
2	0.1052	**0.4763**	0.3859	0.2370	0.1150
3	0.0047	0.1026	**0.2879**	0.3060	0.2400
4	0.0002	0.0099	0.0950	**0.2240**	0.2660
5	0.0000	0.0079	0.0290	0.1650	**0.3520**

Table 5.2: Statistical results from the shower algorithm from 1997 on simulated LAND data as reported in [6]. The values are seemingly not normalized.

Est. \ Energy (MeV)	470	600	1050
1	**0.8484**	**0.7992**	**0.6647**
2	0.1411	0.1829	0.2833
3	0.0097	0.0170	0.0474
4	0.0006	0.0000	0.0043
5	0.0001	0.0000	0.0001
6	0.0000	0.0000	0.0000

Table 5.3: Results from the old shower algorithm currently implemented in land02 for three different energies. The runs are 0257, 0255 and 0263. Even though the results for one neutron events is very good, the algorithm is known to underestimate the number of neutrons in multi neutron events [10]. Unfortunately, this could not be displayed here since the knowledge of how to merge events and then pass them through land02 was insufficient while writing this report.

Chapter 6

Discussion

6.1 Path tracking

The current algorithm produces rather consistent results, but there are differences between runs over the same set of events. The preorder approach for small events produces the exact same results every time, but the ant colony optimization approach is a stochastic method which guarantees running time rather than solution quality.

There is a limiting problem with the current implementation of the ant colony optimization algorithm. In a multi neutron scenario, ants walk between shared hits which have physical constraints such as momentum conservation, causality and similar. It is not uncommon that the tracker can not see possible scenarios when the physical constraints cuts large subtrees of the search space. One solution, the inclusion of ghost hits, will be explained in the next section. Another solution is to grow scenarios not only forward in time, but also backwards, something we did not have time to try.

An alternative search algorithm was brought to our attention by Peter Damaschke in an introductory phase of the E-science project at Chalmers. In principle, it is a slightly more sophisticated version of our preorder search that relies on bound heuristics, a common trick in combinatorial search. Our tracking algorithm would not require a large rewrite to use this algorithm, because only neutron path length is used as a probability function during searches. For a subtree of combinations, the upper and lower bounds can be evaluated by a sort of three dimensional triangular inequality. The upper bound would be the neutron path length probability of the diagonal of the spanning box of hits in a subtree, the lower bound would be the same probability raised to the number of hits.

The other probability functions must be taken into account as well at some point. The scattering angle and momentum distribution functions are only applied on the first hits which is not a problem in this near breadth first approach, but the hit multiplicity requires knowledge of which hits in LAND represent first hits from the neutrons. Since the hit multiplicity is not very easily estimated, we decided not to spend too much time on this algorithm.

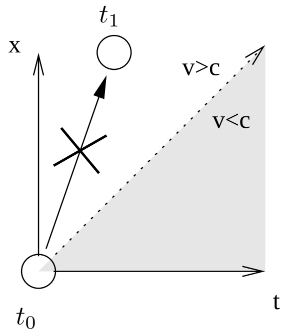

Figure 6.1: Two hits that are not compatible with the principle of causality. If we assume that the first hit at time t_0 would cause the hit at time t_1, then the information between the hits would have to travel faster than the speed of light, which is not compatible with causality. In other words, it is a forbidden path.

6.2 Ghost hits

The discovery of mutually exclusive hits in the S107 data is not a result of crooked preprocessed data used in [8]. These hits are rooted deep in the raw data and deserve to be investigated further. After the new preprocessor, there is still a considerably large amount of hits that break causality, even when the resolution of LAND is taken into account, see Figure 6.1.

The quasi free model has no restrictions whether a neutron would prefer to knock out a proton or another neutron. This preference should be completely related to the ratio of protons and neutrons in the constituents of LAND. With a back of the envelope calculation we see that LAND is about 53 percent neutrons and 47 percent protons, so the probability for a neutron to interact with a certain type of nucleon, given that there is an interaction, is simply

$$\begin{aligned} P(N, N|interaction) &= 0.53, \\ P(N, P|interaction) &= 0.47. \end{aligned}$$

The neutron knockout reaction, which according to the above reasoning is the more probable one, is totally invisible to the detector if it occurs in the iron, and it is hence called a ghost hit. If the same reaction happens in the scintillator, it might be detectable since the neutron knockout will leave the carbon nuclei[1] in an excited state, which will eventually fall down to a lower energy state and emit photons that can be detected by the PM tubes. About 28 percent of the events in the deuteron data have hits that are causally incompatible, demanding a ghost hit to be explained, see Figure 6.2. Whether the remaining 72 percent of the events involve a ghost hit or not is impossible to tell.

Trusting the S107 data, we can do a simple prediction of how the ghost hits would affect multi neutron events. Since there is no way of tracking down ghost hits unless the number of neutrons is known, they will always make the events appear to have more neutrons than they really do. The number of neutrons

[1]A scintillator is a compound of carbon and hydrogen, and since we're looking at neutron knockout reactions, only the carbon nuclei are of interest.

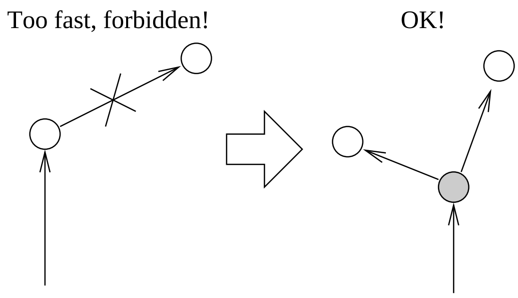

Figure 6.2: To the left are two hits that can not be combined due to the principle of causality. To the right, the two hits can be related by introducing a ghost hit that the detector could not see, for example a neutron only interaction.

counted will always be larger or equal to the true number of neutrons. By taking each neutron of an event, multiplying their probabilities of holding a ghost hit or not, we get the probability for how many neutrons would be counted due to the ghost hits.

$$P(!ghost)^{\#!ghost} \times P(ghost)^{\#ghost} \times \#combinations$$

If we let P be the probability for a ghost hit, N_r be the real number of neutrons of an event and N_c be the number of counted neutrons, we get the following equation

$$(1-P)^{2N_r-N_c} \times P^{N_c-N_r} \times \frac{N_r!}{(N_c-N_r)! \times (2N_r-N_c)!}$$

Applying this to events with up to six neutrons results in Table 6.1. What we see is a distinct shift in the number of counted neutrons. This shift would have been even greater if the probability deduced from the quasi free model had been used. The calculations performed completely ignore the fact that multiple neutron hits can overlap in space and time, which would make hits incompatible with causality compatible and push the shift back.

It should be noted that the currently employed greedy shower algorithm combines hits which are compatible with casuality. Therefore, the statistical effects of ghost hits and the greedy assignment may make it behave correctly on average, but not eventwise.

6.3 Energies in LAND

The amount of photons that the PM tubes in LAND record is proportional to the energy deposited in the scintillator. This energy information could be useful on many levels in the neutron tracker, for instance would energy conservation quickly rule out complete branches in the path tracking, and the momentum distribution probability function would be more precise.

Since the measured energy does not include the energy deposited in the iron, it can only serve as a lower bound of the total energy of the detected particle.

Calc \ Real	1	2	3	4	5	6
1	0.72000	-	-	-	-	-
2	0.28000	0.51840	-	-	-	-
3	-	0.40320	0.37325	-	-	-
4	-	0.07840	0.43546	0.26874	-	-
5	-	-	0.16934	0.41804	0.19349	-
6	-	-	0.0220	0.24386	0.37623	0.13931
7	-	-	-	0.06322	0.29263	0.32507
8	-	-	-	0.00615	0.11380	0.31604
9	-	-	-	-	0.02213	0.16387
10	-	-	-	-	0.00172	0.04780
11	-	-	-	-	-	0.00743
12	-	-	-	-	-	0.00048

Table 6.1: The probability for miscounting the number of incoming neutrons due to ghost hits. The overlap effect is not taken into account.

A way to estimate the true energy of the particle is to use the Bethe formula backwards. This produces stopping power tables for the iron and the scintillator that shows the energy loss for particles of different energies. Assuming that the detected particle comes to rest in a layer of iron, we can use these tables to estimate the energy that it had in the previous layer of scintillator. Continuing this back tracking process, adding the energies that the particle would lose in each layer until the detected energy has been accounted for in the scintillating layers, results in the total energy of the particle.

Unfortunately, the energy information in the S107 experiment is insufficient, so this method could not be used in our algorithm.

6.4 An iron free detector

A way to overcome the problem of particles depositing undetectable energy in the iron would be to build a detector exclusively out of scintillating material, making the detector completely active. This idea has been carried out by the MoNA collaboration at Michigan State University. The MoNA detector is a neutron detector similar to LAND that consists of 16×9 paddles of LAND dimensions, but made completely out of scintillating material. Without the iron, moving charged particles in the detector are completely exposed, and all of their deposited energy can be measured. For a detector without iron to have the same detection efficiency as LAND, it will need to be much larger since the scattering cross section is lower for scintillator than for iron. The price for such a construction would be significantly higher.

Another alternative composition of a neutron detector worth mentioning is the neutron detector at RIBLL in Lanzhou, China. It has very close resemblance to LAND, but the first two layers of paddles have no iron. The purpose of this is to improve the detection efficiency of lower energy neutrons.

6.5 A new deuteron run

Over the years, the status of a detector changes. To develop an algorithm suitable for the current status of LAND, a new deuteron run is required. This would produce more reliable and easily accessible data that would be useful to further investigate ghost hits.

6.6 Dismissed ideas

Almost all of the ideas during the progress of this thesis have been successfully implemented in the algorithm. One less successful main idea was to apply all the probability functions on every part of paths in LAND. Due to the poor resolution of LAND and that the empirical distributions (the momentum, scattering angle and hit multiplicity distributions) are implicit and therefore hard to determine as noted in the algorithm Chapter in Section 4.4, they gave notably erroneous and unreliable results. The idea was dismissed and the empirical probability functions are applied only to paths evolving from the first hit of an incoming neutron, but the neutron path length is still used on all parts of the paths.

Chapter 7

Conclusion

The probabilistic neutron tracking algorithm developed in this thesis is an improvement of the previous shower algorithms. Not only does it deliver better overall statistical results, but it also displays the inner processes of neutron events, which is useful to make sure that hits are assigned correctly.

Better results will require longer run times. A typical LAND run file with little kinetic energy[1] can take a few seconds to process. Runs in the higher energy domain generally have more hits which give significantly longer run times. The running time can be reduced by tweaking the parameters of the ant colony optimization, but we tried to find a set of parameters that would work in most cases.

Implementing the more sophisticated preorder search discussed in Chapter 6.1 to the path tracking will guarantee the best possible solution even for events with 12 or more hits. The current search with ant colony optimization for large events does its job well and is practical with its upper limit on the running time, but in some cases it can miss branches with good solutions.

A brief look at the results from the merged deuteron data presented by the viewer shows capabilities not only to resolve the right number of neutrons for the events, but also to assigns the hits to the right neutron tracks. Hits from the different incoming neutrons can overlap a lot in large events, and the reconstruction of neutron paths tend to fail after the first hit. The number of neutrons and the initial neutron hits is usually correctly determined.

LAND analysis of neutron showers has taken a leap forward with this probabilistic algorithm. The most important next step is to resolve the issue with ghost hits and possibly more concrete handling with the rather limited spatial resolution of LAND. With those issues solved, this probabilistic neutron tracking algorithm could serve LAND, NeuLAND and similar neutron detectors for years to come.

[1] Roughly 30000 events with an average of 3 hits per event after the preprocessor.

Chapter 8

Outlook

8.1 FAIR, R^3B and NeuLAND

As a next step of research at GSI, a large facility to be used for ion and anti-proton research called FAIR is under development. R^3B, an international collaboration of around 50 universities worldwide, is an experimental setup that will be constructed for FAIR. For neutron detection, a detector similar to LAND will be built, called NeuLAND. Prototypes for the neutron detector using RPCs are being tested which will provide superior time resolution but no energy information. Since the energies as reported by LAND were not of particular use for us, the loss of energy information will not be a hard hit although better energy readings would have been helpful. What would be of most use would be dedicated kinematics experiments with the RPCs to construct proper probability functions, rather than relying on generic experiment data as was done for this report.

8.2 E-science

E-science is an initiative picked up by Chalmers which aims to fuse experience in computer science into other fields of research such as physics, chemistry and biology. It is still in early development and this project is one of the first to benefit from the initiative. As was mentioned in the discussion chapter, we learnt about better search methods than preorder pruning from Peter Damaschke. The subject of neutron tracking is not particularly wide, but is nonetheless a problem which needs to be solved.

Acknowledgements

As always, a master's project is hardly a product of the students alone.

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Hans Törnqvist appreciates all the kindness and help from his family members; mother Hiroko for teaching problem solving and generally being clever, father Lars for always being helpful and interested, and older brother Erik for introducing me to all kinds of extraordinary and creative hobbies. Hans would also like to thank all his teachers and lecturers and of course all his good friends over the years.

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Glossary

ACO - Ant Colony Optimization, a stochastic optimization algorithm with guaranteed running time often used to find low cost routes in graphs.

ALADiN - A Large Acceptance Dipole magNet, bends the trajectory of charged particles in the ALADiN-LAND setup at GSI.

CAMAC - Computer Automated Measure And Control.

CERN - Organisation Européenne pour la Recherche Nucléaire, the largest particle physics laboratory in the world.

DAQ - Data AcQuisition.

FAIR - Facility for Anti proton and Ion Research, a large upcoming multi-experiment facility at GSI.

FORTRAN 77 - Ancient programming language suited for high performance physics computations.

GSI - Gesellschaft für Schwerionenforschung, research facility outside Darmstadt in Germany.

LAND - Large Area Neutron Detector, big segmented block of scintillating plastic and iron for neutron moderation.

MATLAB - Well known and established numerical software package for research.

MoNA - Modular Neutron Array, a large area neutron detector housed at the National Superconducting Cyclotron Laboratory at Michigan State University.

NaN - Not A Number, a representation for an undefined value in a computer.

NeuLAND - The new LAND in the R^3B experimental setup.

PAW - Physics Analysis Workstation, predecessor to ROOT.

PM tube - Photomultiplier tube, converts photons into electrons and amplifies the small resulting currents.

QDC - Charge to Digital Converter.

R^3B - Reactions with Relativistic Radioactive Beams, an experiment setup designed for the upcoming FAIR.

RIBLL - Radioactive Ion Beam Line in Lanzhou, a part of the heavy ion research facility of Lanzhou, China.

ROOT - Software package developed at CERN for analysing data from particle physics experiments, successor to PAW.

RPC - Resistive Plate Chamber, gaseous chambers used to detect charged particles.

S107 - Deuteron experiment performed with the ALADiN-LAND setup in 1992 at GSI.

Scintillator - Material producing light when charged particles travel through.

TDC - Time to Digital Converter.

TOF - Time Of Flight wall, positioned at the end of the charged particle trajectory in the LAND setup.

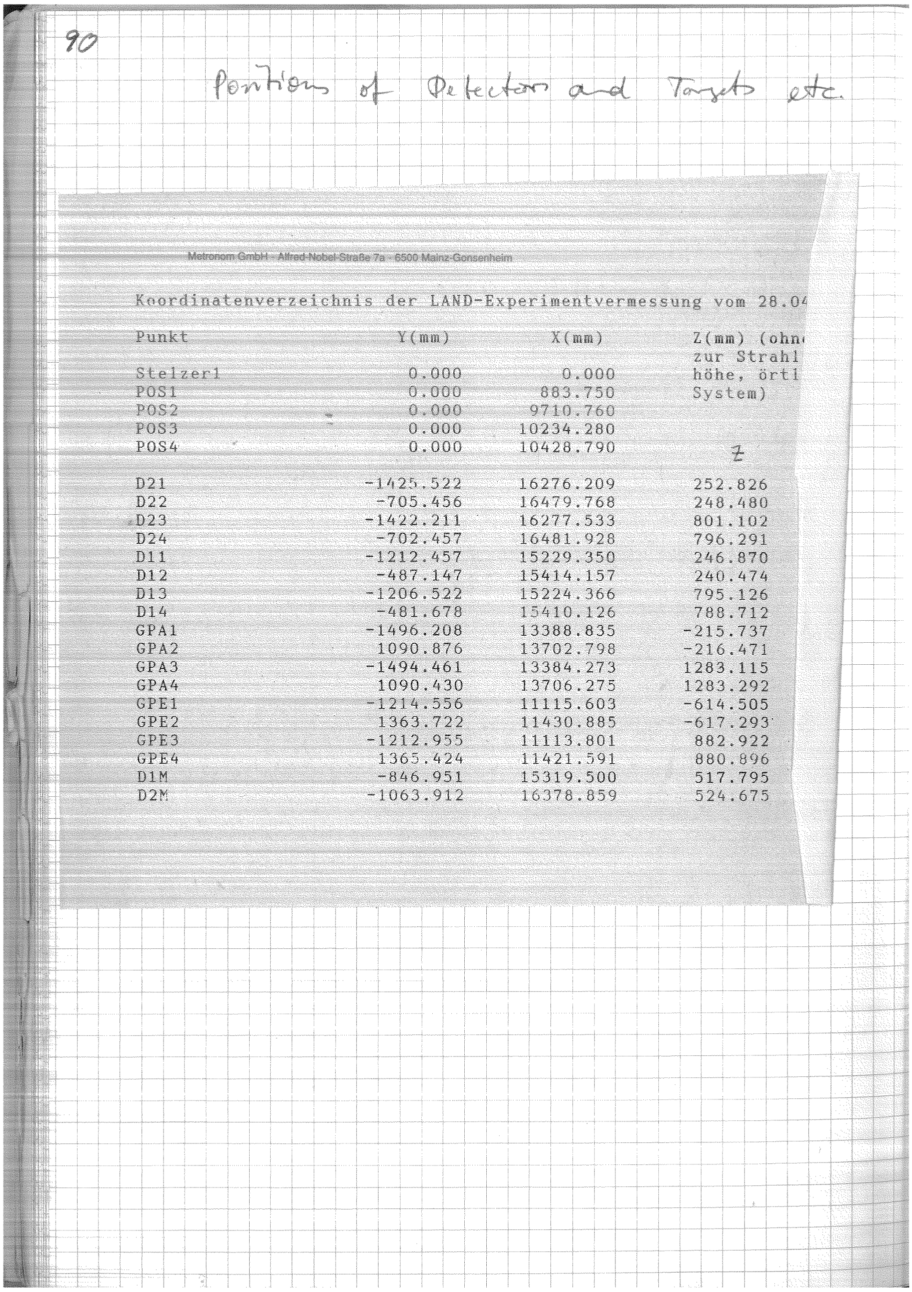
Appendix A

Deuteron run logbook

The following pages shows excerpts from the logbook for the S107 deuteron experiment carried out in 1992 at GSI. Table A.1 lists and explains the trigger pattern bits, and the scanned images show the physical setup for the experiment.

Bit	Meaning
1	GB & Pos2 & $\overline{\text{Halo}}$ & Spill
2	GB & (L+V)
3	d = GB & Pos3
4	p = GB & ToF
5	p & (L+V) [before beam time]
6	cosmic L
7	cosmic V
8	p & (L+V) [during beam time]
9	-
10	laser
11	time calibrator
12	clock
13	end of spill
14	beam focus = Stelzer1
15	-
16	CsJ

Table A.1: Trigger pattern bits for the S107 experiment dug out from the archives at GSI.



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Positions of Detectors and Targets etc.

Metronom GmbH · Alfred-Nobel-Straße 7a · 6500 Mainz-Gonsenheim

Koordinatenverzeichnis der LAND-Experimentvermessung vom 28.04

Punkt	Y(mm)	X(mm)	Z(mm) (ohn zur Strahl höhe, örtl System)
Stelzer1	0.000	0.000	
POS1	0.000	883.750	
POS2	0.000	9710.760	
POS3	0.000	10234.280	
POS4	0.000	10428.790	z
D21	-1425.522	16276.209	252.826
D22	-705.456	16479.768	248.480
D23	-1422.211	16277.533	801.102
D24	-702.457	16481.928	796.291
D11	-1212.457	15229.350	246.870
D12	-487.147	15414.157	240.474
D13	-1206.522	15224.366	795.126
D14	-481.678	15410.126	788.712
GPA1	-1496.208	13388.835	-215.737
GPA2	1090.876	13702.798	-216.471
GPA3	-1494.461	13384.273	1283.115
GPA4	1090.430	13706.275	1283.292
GPE1	-1214.556	11115.603	-614.505
GPE2	1363.722	11430.885	-617.293
GPE3	-1212.955	11113.801	882.922
GPE4	1365.424	11421.591	880.896
D1M	-846.951	15319.500	517.795
D2M	-1063.912	16378.859	524.675

Figure A.1: Measurements of positions of important features in S107 from the logbook.

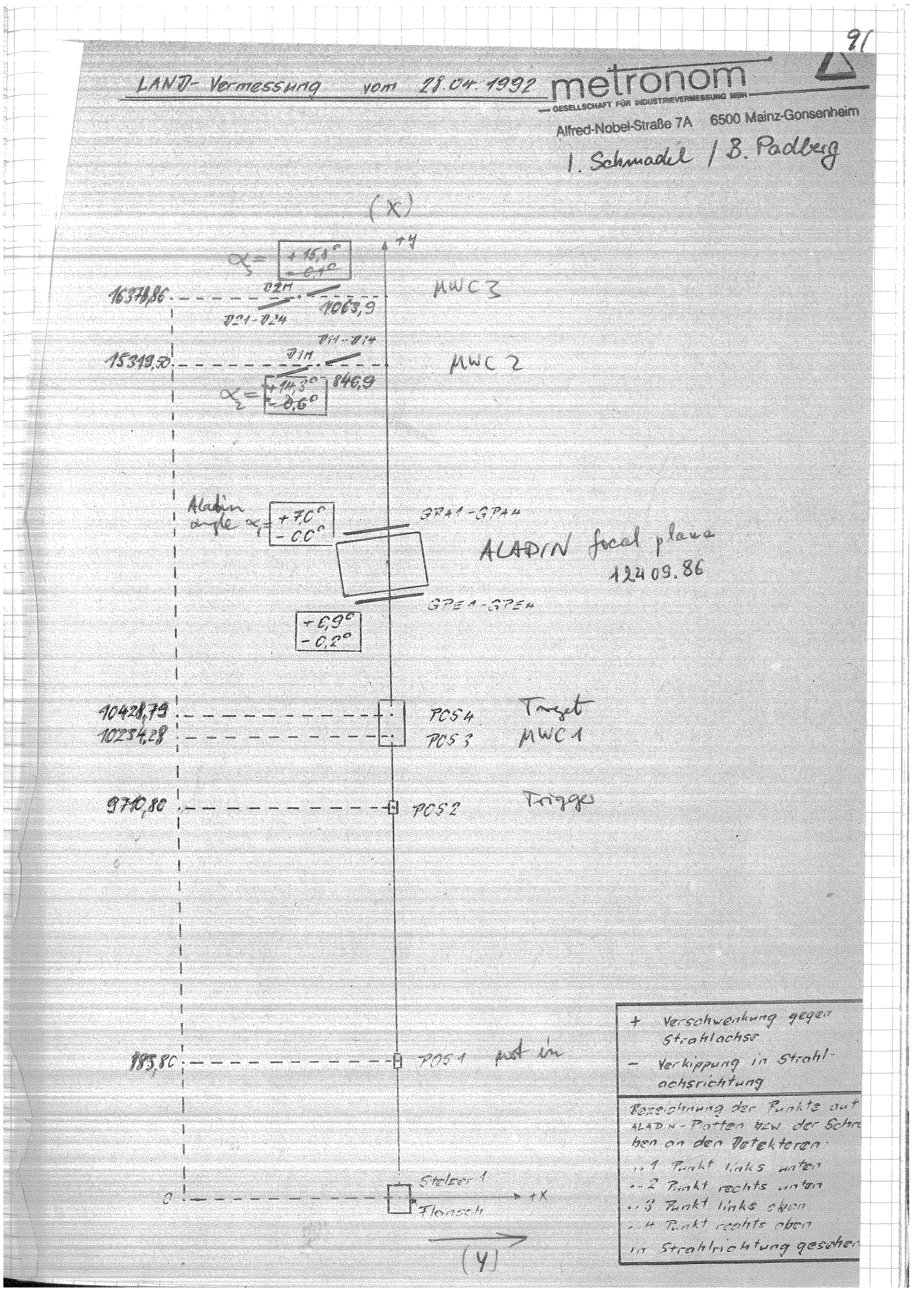
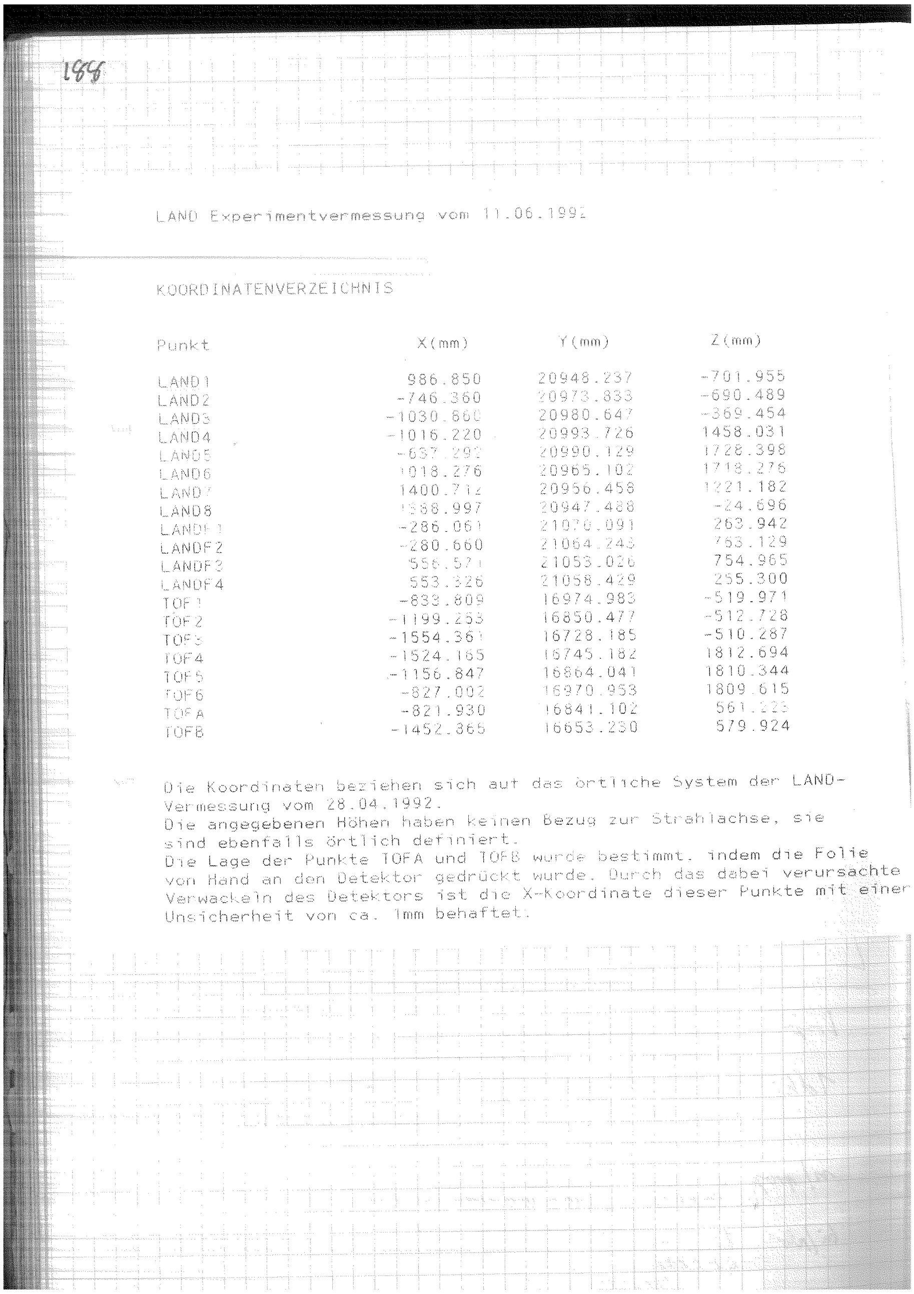


Figure A.2: Hand drawn schematic of S107 from the logbook.



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LAND Experimentvermessung vom 11.06.1992

KOORDINATENVERZEICHNIS

Punkt	X(mm)	Y(mm)	Z(mm)
LAND1	986.850	20948.237	-701.955
LAND2	-746.360	20973.833	-690.489
LAND3	-1030.860	20980.647	-369.454
LAND4	-1016.220	20993.726	1458.031
LAND5	-637.292	20990.129	1728.398
LAND6	1018.276	20965.102	1718.276
LAND7	1400.712	20956.458	1221.182
LAND8	1588.997	20947.488	-24.696
LANDF1	-286.061	21070.091	263.942
LANDF2	-280.660	21064.243	763.129
LANDF3	556.571	21053.026	754.965
LANDF4	553.326	21058.429	255.300
TOF1	-833.809	16974.983	-519.971
TOF2	-1199.253	16850.477	-512.728
TOF3	-1554.361	16728.185	-510.287
TOF4	-1524.165	16745.182	1812.694
TOF5	-1156.847	16864.041	1810.344
TOF6	-827.002	16970.953	1809.615
TOFA	-821.930	16841.102	561.225
TOFB	-1452.365	16653.230	579.924

Die Koordinaten beziehen sich auf das örtliche System der LAND-Vermessung vom 28.04.1992.
Die angegebenen Höhen haben keinen Bezug zur Strahlachse, sie sind ebenfalls örtlich definiert.
Die Lage der Punkte TOFA und TOFB wurde bestimmt, indem die Folie von Hand an den Detektor gedrückt wurde. Durch das dabei verursachte Verwackeln des Detektors ist die X-Koordinate dieser Punkte mit einer Unsicherheit von ca. 1mm behaftet.

Figure A.3: Dimensions of LAND and the TOF wall from the logbook.

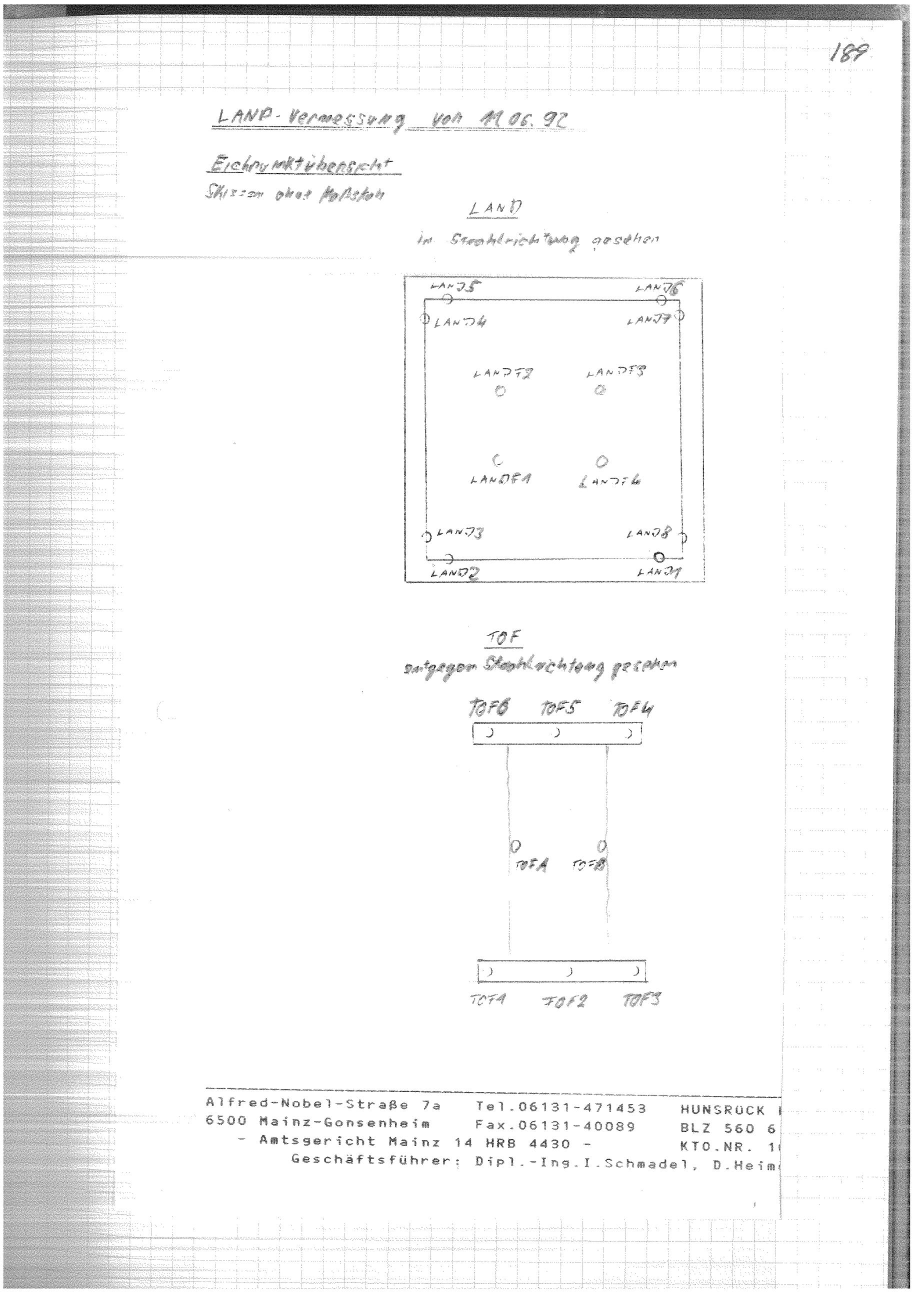

Figure A.4: Hand drawn schematic of LAND and the TOF wall from the logbook.

Appendix B

Neutron path length probability calculations

The neutron path length probability function is based entirely on the neutron scattering cross sections of the building blocks of LAND, which are iron and scintillating plastic. The scintillator used is of BC 408 type and consists only of carbon and hydrogen. For the energy domain of a typical LAND experiment the scattering cross sections for neutrons are practically constant:

$$\begin{aligned}
\sigma(^{56}\mathrm{Fe}) &= 0.85 \text{ b},\\
\sigma(^{12}\mathrm{C}) &= 0.25 \text{ b},\\
\sigma(^{1}\mathrm{H}) &= 0.035 \text{ b},
\end{aligned}$$

where the unit is barn, which equals 10^{-24} cm^2 [9].

The density of ^{56}Fe is 7.85 g/cm^3 and the atomic weight is 55.85 g/mol resulting in $7.85 \div 55.85$ mol/cm^3. The distance between the atoms in a body centred cubic lattice of ^{56}Fe is $2.87 \cdot 10^{-8}$ cm, so one layer of ^{56}Fe atoms will hold $7.85 \div 55.85 \times 2.87 \cdot 10^{-8}$ mol/cm^2, which is equivalent to $7.85 \div 55.85 \times 2.87 \cdot 10^{-8} \times 6.022 \cdot 10^{23}$ atoms/cm^2. With the above given scattering cross sections, the probability for a neutron to interact in one layer of ^{56}Fe atoms will be

$$\begin{aligned}
\mathrm{P}(\text{one layer } ^{56}\mathrm{Fe} \mid \text{int}) &= 7.85 \div 55.85 \times 2.87 \cdot 10^{-8} \times 6.022 \cdot 10^{23}\\
&\quad \times 0.85 \cdot 10^{-24}\\
&= 2.065 \cdot 10^{-9}
\end{aligned}$$

and the probability for a neutron to travel x cm in ^{56}Fe without interacting is

$$\mathrm{P}(x \text{ cm iron} \mid \text{no int}) = (1 \text{ - } \mathrm{P}(\text{one layer } ^{56}\mathrm{Fe} \mid \text{int}))^{x/(2.87 \cdot 10^{-8})}$$

The scintillator has $4.74 \cdot 10^{22}$ ^{12}C atoms/cm^3 and $5.23 \cdot 10^{22}$ ^{1}H atoms/cm^3. If the inter planar distance is $2.76 \cdot 10^{-8}$ cm for the ^{12}C atoms and $2.67 \cdot 10^{-8}$ cm for the ^{1}H atoms, the probability for a neutron to interact in one layer of atoms is

$$\begin{aligned}
\mathrm{P}(\text{one layer } ^{12}\mathrm{C} \mid \text{int}) &= 4.74 \cdot 10^{22} \times 2.76 \cdot 10^{-8} \times 0.25 \cdot 10^{-24}\\
&= 3.27 \cdot 10^{-10}
\end{aligned}$$

$$
\begin{aligned}
\text{P(one layer } ^1\text{H} \mid \text{int)} &= 5.23 \cdot 10^{22} \times 2.67 \cdot 10^{-8} \times 0.035 \cdot 10^{-24} \\
&= 4.89 \cdot 10^{-11}
\end{aligned}
$$

So the probability for a neutron not to interact in x cm of scintillator is

$$
\begin{aligned}
\text{P(}x\text{ cm scintillator} \mid \text{no int)} &= (1 \text{ - P(one layer } ^{12}\text{C} \mid \text{int))}^{x/(2.76 \cdot 10^{-8})} \\
&\quad \times (1 \text{ - P(one layer } ^{1}\text{H} \mid \text{int))}^{x/(2.67 \cdot 10^{-8})}
\end{aligned}
$$

Since x cm of LAND is half scintillator and half iron, the probabilities for no interaction can be combined, yielding the probability for a neutron to interact after x cm in LAND

$$
\begin{aligned}
\text{P(}x\text{ cm LAND} \mid \text{no int)} &= \text{P(}x/2\text{ cm iron} \mid \text{no int)} \\
&\quad \times \text{P(}x/2\text{ cm scintillator} \mid \text{no int)}
\end{aligned}
$$

which is the neutron path length probability distribution in Figure 4.1.

A quick check confirms that we are on the right track, since the probability of an interaction anywhere in LAND is

$$
\begin{aligned}
1 \text{ - P(whole of LAND} \mid \text{no int)} &= 1 \text{ - P(100 cm LAND} \mid \text{no int)} \\
&= 1 \text{ - } 0.014 = 0.986
\end{aligned}
$$

which is consistent with the estimated efficiency of LAND [2].

Appendix C

Preorder search

Branching paths are normally visualised with generic graph structures. If the nodes in the paths can be ordered absolutely, for example by assigning time-stamps, the graph can be ordered and then the paths can be represented in a tree structure, as in Figure C.1.

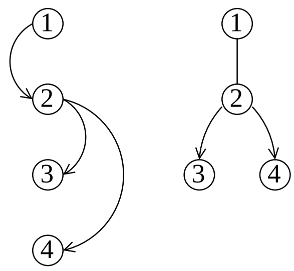

Figure C.1: Going from a graph to a tree. To the left is a graph where the nodes have been laid out in sorted order, to the right is the tree representation.

The term preorder search is used with tree data structures and represents the order in which the nodes of the tree are traversed. The following set of rules are followed:

- Visit the current node.
- Visit the right node.
- Visit the left node.

With the tree representation of paths and preorder search, the search will visit partial paths before full paths. This is useful for early pruning, because bad guesses high up in the tree will not construct full paths if there are other full paths which are better.

One obvious flaw with this method is that at least one full path needs to be known. In the worst case, we can look at successively better paths when searching and then all full paths will be explored. If the remaining part of a full path can be estimated from a partial path by lower and upper bounds, then the search can be improved by growing a set of partial paths simultaneously.

Appendix D

Ant Colony Optimization

Ant Colony Optimization, which will be referred to as ACO from now on, is a stochastic optimization algorithm for finding low cost paths through graphs. The algorithm was invented by Marco Dorigo in 1992 using ideas from how ant colonies can collectively find food and transport it to their nests [12].

Ants deposit pheromones on paths they travel on and will also look for existing levels of pheromones to decide how to choose what paths to follow. Since pheromones evaporate over time, long paths will loose more pheromones than short paths and so short paths will be favoured. The ACO algorithm simulates this collective feature by varying the pheromone levels depending on path cost and a discrete evaporation step when a set of ants have walked. One crucial detail is that ants don't rely entirely on pheromone levels, but make probabilistic choices with pheromones in mind. This allows for some iterative exploration of paths, based on previous low cost paths.

Some pictures may help to better understand the concept. Figure D.1 shows a group of ants looking for food. After having found the food, ants deposit pheromones depending on the length of their paths, visualised in D.2. Pheromones are evaporated and then ants choose paths depending on the available pheromones, in Figure D.3.

Since this algorithm is designed to find paths of low cost between branch points, it can be slightly altered to find paths with high accumulated probability

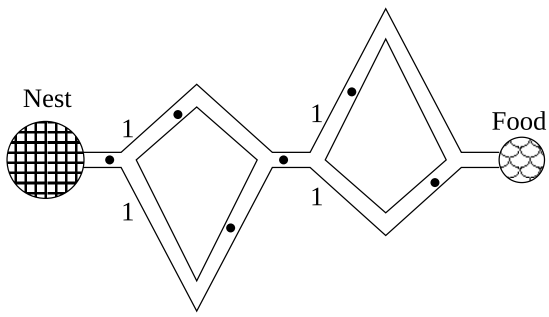

Figure D.1: Ants on the hunt for food. The numbers denote the relative probability weight that the corresponding path will be chosen by ants.

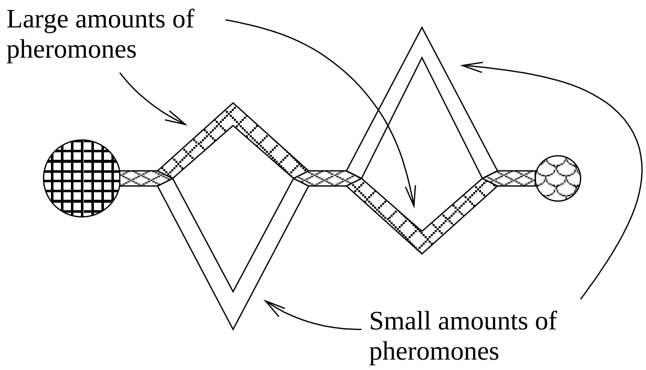

Figure D.2: Ants have found food and have deposited pheromones based on their path lengths.

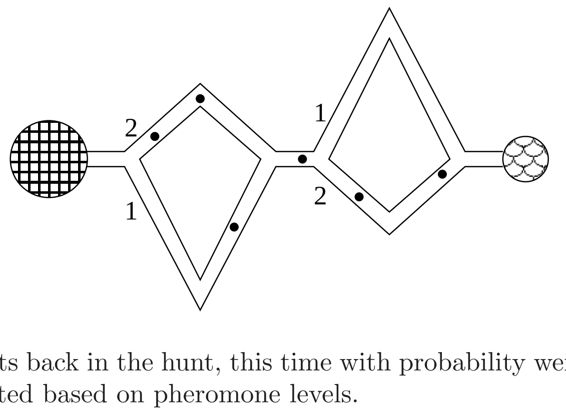

Figure D.3: Ants back in the hunt, this time with probability weights for choosing paths updated based on pheromone levels.

between detector hits. One ant represents one neutron in one event, meaning there can be several ants at once trying to construct scenarios for an event. Path cost is estimated from the probability functions explained the tracking algorithm chapter, including the path from the target to the neutron detector.