

# I DID SOMETHING COOL AT CERN - ISOLDE

by

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THESIS

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MASTER OF SCIENCE



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# Abstract



To my family, for all their support and encouragement!



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My family

Morten, Alex and Astrid.

Ina, I love you.

## Collaboration details

The sorting and analysis code used in this thesis has been developed at CERN-ISOLDE and can be found at <https://github.com/Miniball/MiniballCoulexSort>

The code for theoretical predictions of energy used in the calibration was developed by Liam Gaffney who is working at ISOLDE and has to do with analysis of data from Miniball and ISS. kinsim can be found here <https://github.com/lpgaff/kinsim>

Some calibration code is based on the codes of Ville Virtanen and Liam Gaffney.

Other code/scripts have been written by the author. C++ / Python.

*Trond Wiggo Johansen*

September, 2019





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# Chapter 1

## Introduction

Test [1]

Test 2 [? ]

kinsim [2]

The experiment has been done before, with lower energy (and another target), Malin Klintefjord. <http://urn.nb.no/URN:NBN:no-56121>

Experiment conducted 8th - 14th of August 2017.



# Chapter 2

## Theory?

Quadrupole deformation of nuclei.

Shape coexistence possible for certain regions of  $N$  and  $Z$ .

- triaxial shape / shape coexistence
- benchmark for theoretical models
- transition probabilities and quadrupole moments between several excited states are not known
- fundamental research



# Chapter 3

## Coulomb excitation experiment

Table of abbreviations and symbols?

**Table 3.1:** Acronyms and abbreviations.

CERN	European Council for Nuclear Research (in French Conseil Européen pour la Recherche Nucléaire)
ISOL	Isotope Separator On Line
ISOLDE	Isotope Separator On Line DEvice
PSB	Proton Synchrotron Booster
GPS	General Purpose Separator
HRS	High Resolution Separator
EBIS	Electron Beam Ion Source
REXEBS	Radioactive beam EXperiment EBIS
RILIS	Resonance Ionization Laser Ion Source
HIE-ISOLDE	High Intensity and Energy upgrade
RIB	Radioactive Ion Beam
ENSAR2	European Nuclear Science and Applications Research - 2
Linac	Linear accelerator
ADC	Analog-to-Digital Converter
TDC	Time-to-Digital Converter (or time digitizer)
Coulex	Coulomb excitation

Why CoulEx? [https://iks32.fys.kuleuven.be/wiki/brix/images/5/58/10\\_20151123\\_Illana\\_BriX15\\_web.pdf](https://iks32.fys.kuleuven.be/wiki/brix/images/5/58/10_20151123_Illana_BriX15_web.pdf)

- nucleus excited by electromagnetic interaction.
- de-excitation  $\rightarrow$  gamma

**Oppgavens mål:**

The ISOLDE facility at CERN has been upgraded to provide higher energies

and intensities for radioactive ion beams. A new experiment to study  $^{140}\text{Sm}$  was performed in the summer of 2017. The goal of the experiment was to measure electromagnetic transition probabilities and electric quadrupole moments for several excited states in  $^{140}\text{Sm}$  by measuring Coulomb excitation probabilities. A large data set was obtained using silicon detectors to determine the energies and angles of scattered particles, and germanium detectors to measure gamma rays from excited states in  $^{140}\text{Sm}$ .

The goal of the master thesis is to analyze the data from this experiment. The required tasks include development and improvement of data analysis software to determine Coulomb excitation yields. These yields will then, in a second step, be compared to theoretical calculations and transition probabilities and quadrupole moments will be extracted using chi-square minimization procedures.

#### Prosjektbeskrivelse (omfang 60 studiepoeng):

The shape of an atomic nucleus is determined by a delicate interplay between macroscopic (liquid drop) properties and microscopic shell effects. Nuclei with filled proton or neutron shells (i.e. magic nuclei) are generally spherical in shape, whereas nuclei with open shells gain energy by assuming a deformed shape. Depending on the occupation of specific orbitals, the nuclear shape can change drastically by adding or removing protons or neutrons. Certain nuclei exhibit shape coexistence, i.e. the coexistence of quantum states that correspond to different shapes. Because the shape of a nucleus is so sensitive to the underlying nuclear structure and to changes of the proton and neutron numbers, the excitation energy, or the angular momentum, observables related to the nuclear shape are used as benchmarks for theoretical models.

Nuclei in the rare earth region, and in particular the chain of samarium isotopes, exhibit a variety of shape effects. The Sm isotope with closed neutron shell at  $N=82$ ,  $^{144}\text{Sm}$ , is spherical in shape. Adding neutrons to  $^{144}\text{Sm}$  changes the deformation to an elongated (prolate) quadrupole shape. The transition from spherical to prolate shape, which occurs for  $^{152}\text{Sm}$  at  $N=90$ , can be interpreted as a shape-phase transition. Flattened (oblate) quadrupole shapes are predicted by theory to occur below the  $N=82$  shell closure. An earlier experiment studying  $^{140}\text{Sm}$  at CERN-ISOLDE found triaxial shape for this isotope, i.e. a shape where all three principal axes of the ellipsoid have different lengths.  $^{140}\text{Sm}$  can therefore be considered to lie at the critical point of a phase transition from spherical to deformed, and from prolate to oblate shape.

#### Foreløpig tittel:

Coulomb excitation of  $^{140}\text{Sm}$

#### Metoder som tenkes benyttet:



Multi-step Coulomb excitation with radioactive beam, isotope separation on-line technique, nuclear spectroscopy, particle-gamma and particle gamma-gamma coincidence analysis, advanced chi-square minimization procedures.

## 3.1 ISOLDE at CERN

ISOLDE is a radioactive ion beam facility at CERN in Meyrin, Switzerland. The facility can produce over 1000 different radionuclides to be used in a wide variety of experiments in nuclear physics, atomic physics, solid state physics, life sciences and fundamental interactions. Experiments have been performed at ISOLDE since 1967 and since 2001 experiments with post-accelerated radioactive ion beams (RIBs) have been conducted. **New / moved facility in 1992, to the place as we know it today.** The high intensity and energy upgrade (HIE-ISOLDE) have made it possible to deliver energies up to 10 MeV/u in 2018 [? ]. **Cite:** <http://iopscience.iop.org/article/10.1088/1361-6471/aa990f> and [http://www.scholarpedia.org/article/The\\_ISOLDE\\_facility](http://www.scholarpedia.org/article/The_ISOLDE_facility)

ISOLDE <http://isolde.web.cern.ch> and [http://isolde.web.cern.ch/sites/isolde.web.cern.ch/files/NuclPhysNew-ISOLDE\\_0.pdf](http://isolde.web.cern.ch/sites/isolde.web.cern.ch/files/NuclPhysNew-ISOLDE_0.pdf) and [http://www.scholarpedia.org/article/The\\_ISOLDE\\_facility](http://www.scholarpedia.org/article/The_ISOLDE_facility) and <http://iopscience.iop.org/article/10.1088/1361-6471/aa5f03/pdf>

HIE-ISOLDE <http://hie-isolde-project.web.cern.ch>, technical design <http://cds.cern.ch/record/2635892?ln=en>, direct to doc: [http://cds.cern.ch/record/2635892/files/HIE-ISOLDE\\_TDR.pdf](http://cds.cern.ch/record/2635892/files/HIE-ISOLDE_TDR.pdf)

### 3.1.1 Beam production

ISOLDE experimental hall (**make flow chart or show overview over the hall**):

$p^+$  (from PSB)  $\rightarrow$  Production target  $\rightarrow$  GPS  $\rightarrow$  RILIS  $\rightarrow$  **REXTRAP?**  $\rightarrow$   
REXEBS  $\rightarrow$  HIE-ISOLDE  $\rightarrow$  MINIBALL

A proton beam of 1.4 GeV ( $\sim 10^{18}$  protons) from the PSB comes into the ISOLDE facility and collide with a production target **of tantalum, producing the elements in the chart of nuclides up to tantalum.** The proton beam can collide in one of the two target stations, the general purpose separator (GPS) or the high resolution separator (HRS). The GPS has one bending magnet and can deliver beams of different mass simultaneously into three beam lines, while the HRS has two bending magnets with high mass resolving power and deliver the beam into the main **(or common)** beam line. In this experiment, the GPS was used. The

fragments travels in the beam line onward to the GPS where the mass of  $A = 140$  (isobar) is selected (separated from the rest).

GPS or RILIS first??

RILIS or REXEBIS for ionization of the atom?

The resonance ionization laser ion source (RILIS) uses the method of step-wise excitation and ionization of the atom. It is a three step excitation, where the last step leads to the ionization. RILIS selects samarium with laser (element selective process, samarium  $Z = 62$ ). RILIS is used to produce ion beams of the correct element.

REXTRAP. Penning trap

REXEBIS excites the nucleus in three steps ionizing the atom, which leaves the nucleus in a high charge state.

The HIE-linac accelerates the beam through the beam line and magnets bend the beam into MINIBALL.

Cite: [https://ac.els-cdn.com/0168583X92959079/1-s2.0-0168583X92959079-main.pdf?\\_tid=0ccb0647-5870-48f9-ac38-df8c0077981c&acdnt=1545216224\\_d359ddcc40ea1f94369c85](https://ac.els-cdn.com/0168583X92959079/1-s2.0-0168583X92959079-main.pdf?_tid=0ccb0647-5870-48f9-ac38-df8c0077981c&acdnt=1545216224_d359ddcc40ea1f94369c85) and [https://cds.cern.ch/record/2025701/files/epjconf\\_inpc2013\\_11005.pdf](https://cds.cern.ch/record/2025701/files/epjconf_inpc2013_11005.pdf) and <http://isolde.web.cern.ch/targets-and-separators>

"The General Purpose Separator (GPS) has one bending magnet and an electrostatic switchyard allowing the simultaneous extraction of three mass separated beams." <http://isolde.web.cern.ch/targets-and-separators>

ISOLDE GPS++ [https://cds.cern.ch/record/2025701/files/epjconf\\_inpc2013\\_11005.pdf](https://cds.cern.ch/record/2025701/files/epjconf_inpc2013_11005.pdf)

"The RILIS is a chemically selective ion source which relies on resonant excitation of atomic transitions using tunable laser radiation." <http://rilis.web.cern.ch>

"The principal application of RILIS is the production of ion beams of elements required for ISOLDE experiments. ... laser ionization is required to be only an element-selective process" <http://iopscience.iop.org/article/10.1088/1361-6471/aa78e0>

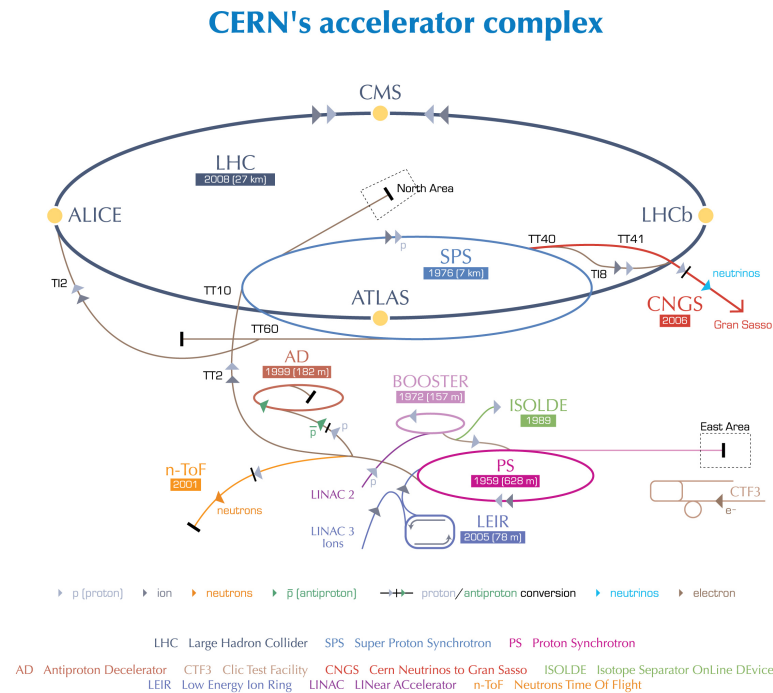
Figure 3.1 shows the CERN accelerator complex [3]. ISOLDE is located beside the PSB.

Magnets....

Ebis: charge breeder: release beam with certain energy.

high-performance charge breeder (CB). CB based on the Electron Beam Ion Source (EBIS) technology – an EBIS Charge Breeder (ECB)

HIE-ISOLDE (Superconducting Linac Upgrade): Linear accelerator, HIE-linac



European Organization for Nuclear Research | Organisation européenne pour la recherche nucléaire

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**Figure 3.1:** The CERN accelerator complex. ISOLDE gets accelerated protons from LINAC 2 and the PS BOOSTER.

Post-accelerated beams ISOLDE <http://iopscience.iop.org/article/10.1088/1361-6471/aa78ca>

ISOLDE actually uses the most protons at CERN [ref?].

Very pure beam (did we have statistics of this?)

PSB <https://home.cern/science/accelerators/proton-synchrotron-booster>

REX-ISOLDE <http://rex-isolde.web.cern.ch>

RILIS <http://rilis.web.cern.ch> and <http://iopscience.iop.org/article/10.1088/1361-6471/aa78e0/meta> and [https://www.research.manchester.ac.uk/portal/files/60831252/FULL\\_TEXT.PDF](https://www.research.manchester.ac.uk/portal/files/60831252/FULL_TEXT.PDF) and <https://www.sciencedirect.com/science/article/pii/S0168583X13008914?via%3Dihub>

MINIBALL <http://isolde.web.cern.ch/experiments/miniball> and [https://www.miniball.york.ac.uk/wiki/Main\\_Page](https://www.miniball.york.ac.uk/wiki/Main_Page)

ENSAR2 <http://www.ensarfp7.eu>

Beam production [http://tuprints.ulb.tu-darmstadt.de/4599/1/TUDthesis\\_Christoph%20Seiffert.pdf](http://tuprints.ulb.tu-darmstadt.de/4599/1/TUDthesis_Christoph%20Seiffert.pdf)

Test [3], copyright: <https://copyright.web.cern.ch>

CERN Document Server <https://cds.cern.ch>

### 3.1.2 Target

$^{208}\text{Pb}$  was chosen as a target. Want high  $Z$  so that the probability of excitation is high. Not enough beam energy to excite  $^{208}\text{Pb}$ .

Highest  $Z$  for maximum excitation probability.

Contamination... finger print [\[picture\]](#)

## 3.2 Miniball

Pictures <https://cds.cern.ch/record/844871?ln=en>

### 3.2.1 Particle detector, DSSSD (CD)

16 rings, 12 strips effectively (24 strips, 12 pairs with two strips making a pair)  
Angle coverage:  $[18.4^\circ, 56.6^\circ]$

### 3.2.2 $\gamma$ detectors, HPGe

24 six-fold segmented. 8 clusters of 3 crystals each. Each crystal segmented in 6 parts (144 segments in total).

Cryo-modules

## 3.3 Experimental setup

$^{140}\text{Sm}$  Coulomb excitation experiment.

Experiment code: IS558

Ta: tantalum ( $Z = 73$ )

Sm: samarium ( $Z = 62$ )

Pb: lead ( $Z = 82$ )

Beam:  $^{140}\text{Sm}$  ( $T_{1/2} \approx 15$  min, 4.65 MeV/ $u$ , total 651 MeV), excellent purity

Target:  $^{208}\text{Pb}$  (Thickness: 1.4 mg/cm<sup>2</sup>)

Small angle: Forward scattering: Larger distance, weaker **EM**-field, less excitation probability.

Large angle: Backward scattering: Closer distance, stronger **EM**-field, higher excitation probability.

Expect to measure transition probabilities  $B(E2)$  and quadrupole moment (nuclear deformation).

Level scheme (from Klintefjord?)



# Chapter 4

## Data analysis

ROOT: analysere data

kinsim3 <https://github.com/lpgaff/kinsim> + SRIM <http://www.srim.org>

**Table 4.1:** Computer used for data analysis

Model	MacBook Air (13-inch, 2017)
Processor	1.8 GHz (Intel Core i5)
Memory	8 GB (1600 MHz DDR3)

Runtime for sorting data:

TreeBuilder (online calibration):  $\sim 40$ -45 min

AQ4Sort (online calibration):  $\sim 120$  min

**Table 4.2:** Runtime for sorting data.

Executable	Runtime [min]
TreeBuilder	$\sim 45$
AQ4Sort	$\sim 120$

The runtime of the bash script was done with the built in script time

```
$ time ./AQ4S.sh Sm online TB
...
real 45m19.265s
user 42m49.653s
sys 0m39.665s
```

```
$ time ./AQ4S.sh Sm online Q4
...
real 121m40.830s
```

```
user 116m18.361s
sys 1m17.809s
```

```
$ time ./AQ4S.sh Sm user TB
...
real 41m11.282s
user 39m45.592s
sys 0m27.777s
```

```
$ time ./AQ4S.sh Sm user Q4
...
real 143m47.600s
user 128m6.174s
sys 1m50.921s
```

particle-gamma and particle-gamma-gamma coincidence  
sjekk opp om energi fra online kalibrering passer med simuleringen.

## 4.1 Data and sorting

The analysis code for Miniball data is named MiniballCoulexSort and is available on GitHub at <https://github.com/Miniball/MiniballCoulexSort>. The main steps of how to download, install and use it is outlined in the README.md file in the GitHub repository.

Data from Miniball comes in the form of .med-files (Miniball Event Data). In order to analyze this data in ROOT<sup>1</sup> the first part of the sorting is just to convert the .med-files into .root-files with the script MedToRoot.

To get useful information out of the converted .root-files, the Treebuilder script is used. The .root-file(s) and a calibration file is given to the Treebuilder so it can make event trees that can be used for analyzing the Coulomb excitation events.

One script that is mentioned in the Miniball GitHub repository, but not showed how to use, is the AQ4Sort. It is used in the same way as the TreeBuilder script, but it sorts the histograms in another way. This script is used before and during the calibration of the detectors, because it gives information about every single ring and every single back strip. The one thing to note here, is that the numbering of the detector rings and strips are different from the ones used in Treebuilder.

---

<sup>1</sup>ROOT is a data analysis framework made at CERN.



## 4.2 Helping scripts

All of my scripts are available in the GitHub repository <https://github.com/wiggoen/MasterThesis>.

In order to not copy and paste the sorting command in the terminal for every data file, I made two bash scripts to do this. The script **M2R.sh** is using MedToRoot to take in as many files as you want, and sort it in one go. The other script is **AQ4S.sh**, which is using either AQ4Sort or Treebuilder to sort a lot of files in one go.

I also made other helping scripts to get histograms, do fitting, comparison and calibration.

My scripts: MultiFit.cpp, MultiPlot.cpp, ++ (python, bash,...)

## 4.3 Simulation

To calibrate the data, we need to know the expected energy of the centroids of the peaks. This was done by simulating the experiment in a program called kinsim3. The program is written by Liam Gaffney<sup>2</sup> and the purpose of the program is to simulate the kinematics of the experiment. It takes into account the Silicon dead layer.

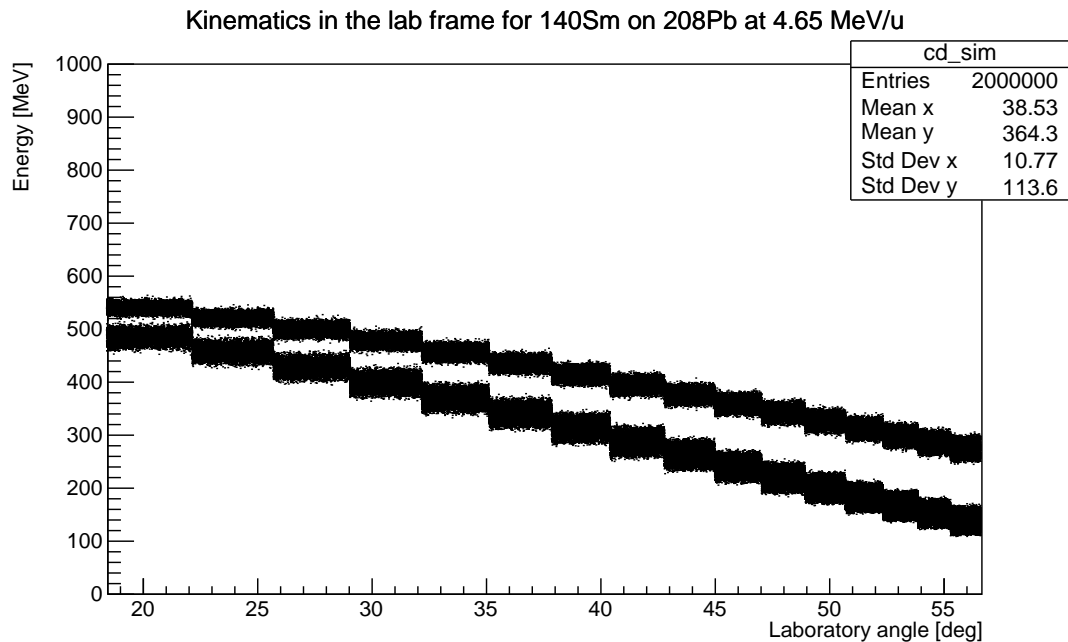
kinsim3 generates pdf-files of the stopping powers automatically. The rest of the plots are available inside the root-file. To get the energy simulation for each ring, the function `cd_sim_plots()` from the script **MultiPlot.cpp** was used.

CD to target distance: 26.98 mm.

Simulation done by kinsim3

---

<sup>2</sup>Liam Gaffney is a fellow at ISOLDE, affiliated with MINIBALL.



**Mail fra Liam:**

”the source has a thickness of 1.23 mm, which needs to be factored in so that the CD to target distance is the CD to source distance PLUS the source thickness, i.e. 25.78 mm + 1.23 mm = 27.01 mm. This is very close to the 26.98 mm you got from us in August. **I think that the source data was reanalysed since the original blog entry, giving the 0.03 mm difference!**”

Terminal: Simulation:  $^{140}\text{Sm}$  on  $^{208}\text{Pb}$ :

```
$ cd GitHub/Miniball/kinsim
$ root
root [0] .L kinsim3.cc+
root [1] kinsim3(62, 82, 140, 208, 1.4, 4.65, 0.02, 1.0, 0.6,
    27.01, false, 1e6, "../SRIM")
```

kinsim3 function:

```
void kinsim3( int Zb, int Zt, double Ab, double At, double
    thick /* mg/cm^2 */, double Eb /* MeV/u */,
    double dEb = 0.1 /* MeV/u */, double Ex = 1.0 /* MeV */,
    double res = 0.6 /* % */,
    double cd_dist = 28.0 /* mm */, bool flat = false /* angular
    distribution? */,
    long Nevts = 1E6, string srim_dir = "../srim" )
```

**Say something about SRIM files.**

## 4.4 Calibration

For each file converted with MedToRoot, the program makes four files; OffBeam, OnBeam, OnBeamBackground and Scaler. The file we are interested in for analysis is the OnBeam file.

First all of the interesting files are converted with the M2R.sh script. Then the OnBeam files from M2R.sh is run through using Treebuilder in the AQ4S.sh script. Using the MultiPlot.cpp script, the ADC time offsets can be extracted by the following commands

```
$ cd /Users/trondwj/GitHub/MasterThesis/Scripts/plotting
$ root
root [0] .L MultiPlot.cpp
root [1] check_ADC_time_offsets("setup_Sm.txt", "user")
```

or they can be manually reached by

```
$ cd /Users/trondwj/GitHub/MasterThesis/Sorted_data
$ root Sm_user-TreeBuilder-2019-03-22.root
root [1] new TBrowser()
```

and in the browser, the histograms named `tdiff_gp.i` (where *i* is a number between 0 and 3) will lie under all the folders.

**HUSK:** Si noe om ADC time offsets. Og at man må se på det tidlig, så resortere.

M2R.sh → AQ4S.sh → check time offset → threshold → AQ4\_fit() → particle-calibration.py → ADC-generator.py → copy the calibration from the terminal and paste into calibration file

Simulation fit → AQ4\_fit() → particle-calibration.py → ADC-generator.py → copy the calibration from the terminal and paste into calibration file

Visualize plots using ROOT and the scripts.

Skriv om scriptene som er lagd, og at det var litt vanskelig å automatisere kalibreringen. Hvis det skulle vært gjort måtte vi funnet en "left skewed function".

I log-skala ser dette mer Gaussisk ut, men det er ikke det i non-log skala.

Back detector calibration: There are just too much individual differences to calibrate the back detectors with a simple script given a range for all 12 back strips. I found out this way to late. There isn't any range to rule them all, at least since the fitting function can behave very strange given a too small or too big range.

### 4.4.1 ADC time offsets

### 4.4.2 Threshold

\* Threshold (forskjellig i log/ikke-log skala)

Threshold: The code has a default threshold of 100, but in some cases this is too much and some cases this is not enough. So for each adc channel, the threshold can be set. We don't want to include the "pedestal". Charge sharing. Won't cut too much or too little..

Sjekk hva Liam skrev i mailen.

### 4.4.3 Particle detector

#### Online calibration

#### User calibration

ADC: Analog to digital converter (Mesytec)

TDC: Time to digital converter

DSSSD: Double-Sided Silicon Strip Detector  $\implies$  CD

must remove the inner ring from data analysis because of damage

$$gain = \frac{E_{Sm} - E_{Pb}}{Ch_{Sm} - Ch_{Pb}}$$

$$offset = E_{Sm} - gain \cdot Ch_{Sm}$$

in keV.

Hvis man har flere sentroider bruker man bare lineær regresjon. Gjelder for baksiden!

### 4.4.4 Gamma detectors

DGF: Digital  $\gamma$  finder

addback, singles, ...

## 4.5 Doppler correction

## Chapter 5

### Experimental results



# Chapter 6

## Discussion





## Chapter 7

### Summary and outlook



# Appendices



# Appendix A

## Connecting MiniballCoulexSort with ROOT

To connect MiniballCoulexSort with ROOT you need them to share their libraries with each other. This is done with a dynamic loader. You can find out more here: <https://root.cern.ch/root/html/doc/guides/users-guide/ROOTUsersGuide.html#file-system.rootrc>.

You have to make a **.rootrc** file in your home folder on your computer. In the **.rootrc** file you want to write something like this

```
Unix.*.Root.DynamicPath:    .:</Users/trondwj/GitHub/ROOT-  
framework/build/lib >:/Users/trondwj/GitHub/Miniball/  
MiniballCoulexSort/lib:
```

This should all be in one line. The first part is to tell the system to use the dynamic loader of ROOT to connect the given paths that follow. In my case the lib folder of the ROOT install was at

```
/Users/trondwj/GitHub/ROOT-framework/build/lib
```

and the lib folder of the MiniballCoulexSort was at

```
/Users/trondwj/GitHub/Miniball/MiniballCoulexSort/lib
```

These paths is totally individual, and you will probably not have it in the same place. Therefore these paths must be changed to fit your system.

After making the file you either have restart the terminal or you can source the file by writing this in the terminal

```
$ source ~/.rootrc
```



## Appendix B

# Running ROOT and MiniballCoulexSort from anywhere in the terminal

To run ROOT or the different scripts of MiniballCoulexSort anywhere in the terminal, you have to edit your **.bash\_profile** file [.bash\_profile on MacOS, .bashrc on Linux]. In my **.bash\_profile** I used this

```
# Run ROOT from anywhere
export ROOTSYS=$HOME/GitHub/ROOT-framework/build
export PATH=$ROOTSYS/lib:$PATH
export PATH=$ROOTSYS/bin:$PATH
export DYLD_LIBRARY_PATH=$ROOTSYS/lib:$DYLD_LIBRARY_PATH

# Run MiniballCoulexSort from anywhere
export DYLD_LIBRARY_PATH=$HOME/GitHub/Miniball/MiniballCoulexSort/lib:$DYLD_LIBRARY_PATH
export PATH=$HOME/GitHub/Miniball/MiniballCoulexSort/lib:$PATH
export PATH=$HOME/GitHub/Miniball/MiniballCoulexSort/bin:$PATH
```

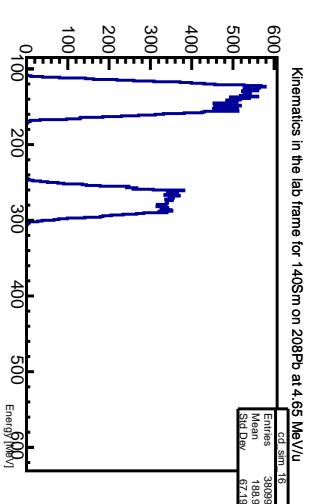
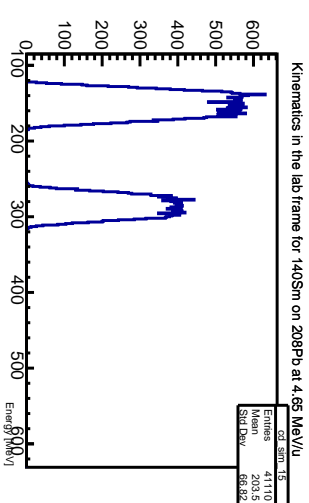
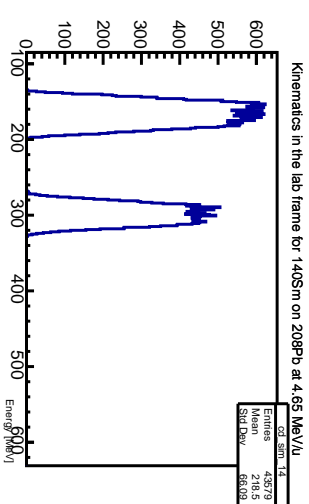
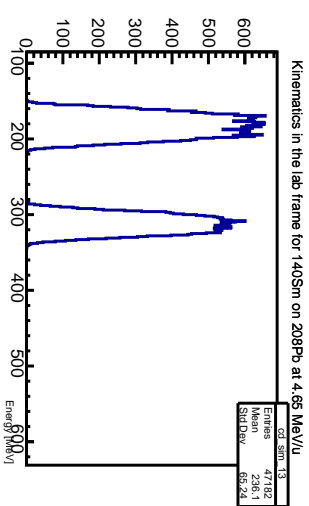
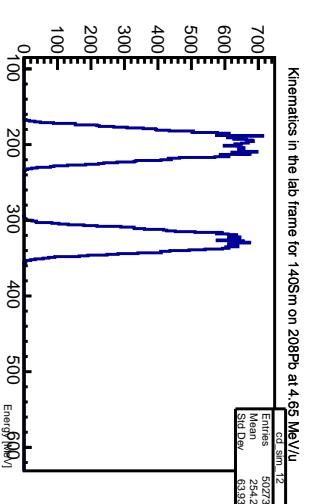
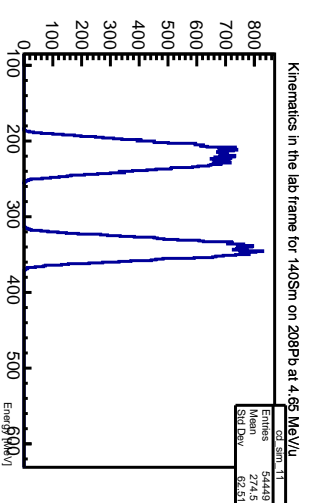
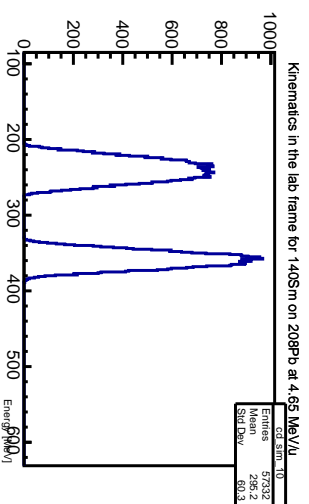
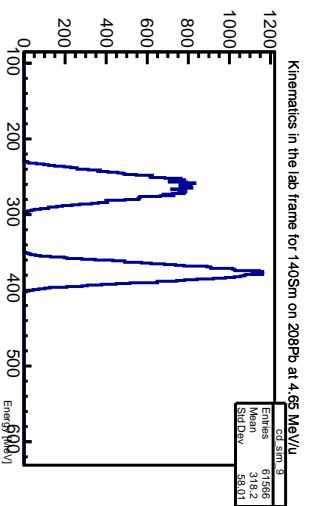
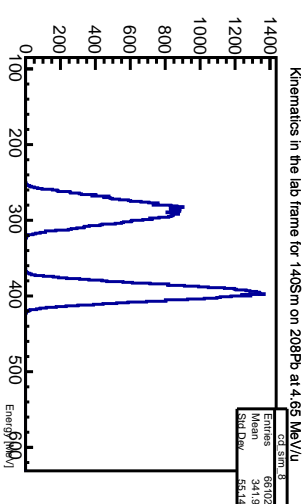
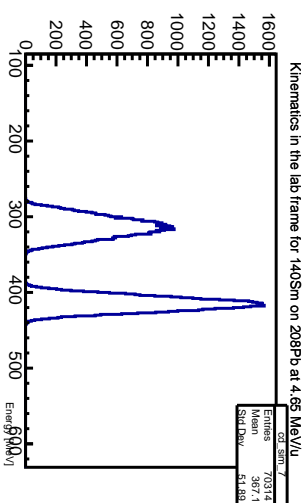
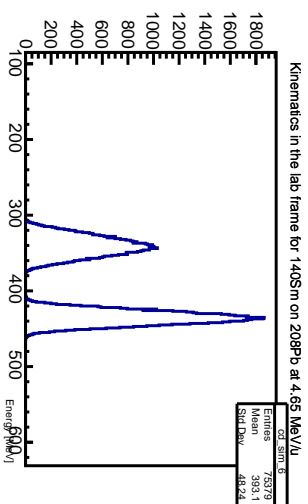
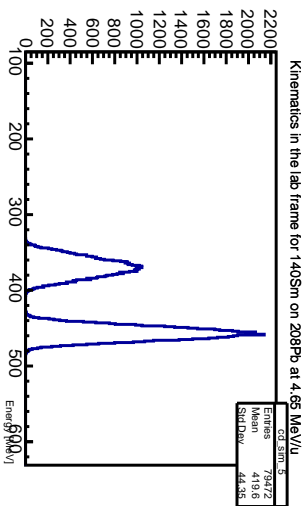
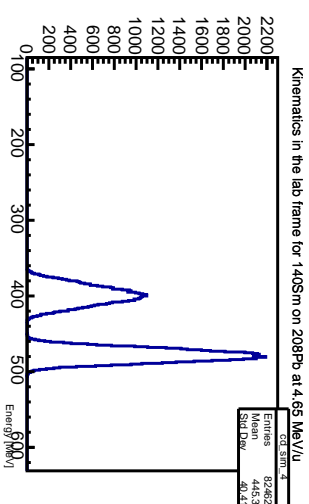
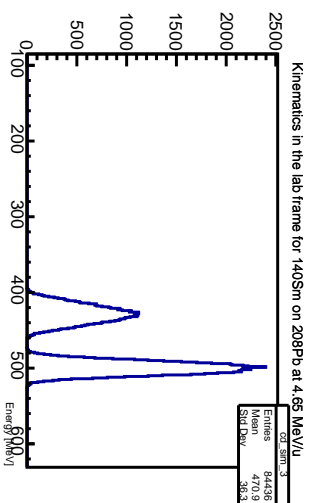
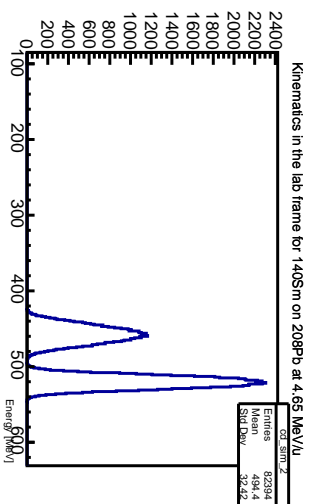
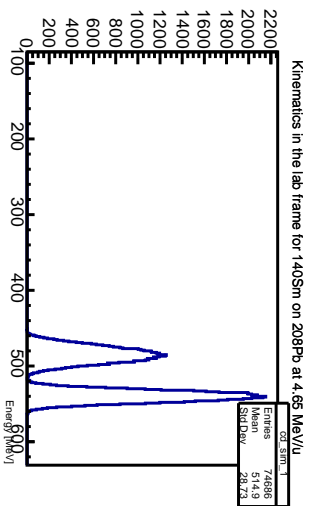
The DYLD\_LIBRARY\_PATH is used on Mac only. On other systems, use LD\_LIBRARY\_PATH. You need to locate the lib and bin folders for both ROOT and MiniballCoulexSort and change them to fit your system, and in addition you need the build folder of your ROOT install.





## Appendix C

### Other appendices



# Bibliography

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- [2] L. Gaffney. Kinematics simulations for Coulomb-excitation experiments at Miniball, May 2018. URL <https://github.com/lpgaff/kinsim>.
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