I did something cool at CERN - ISOLDE

by

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Thesis

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Abstract

To my family, for all their support and encouragement!

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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

Contents

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
REXEBIS	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

- nucleus excited by electromagnetic interaction.
- de-excitation → 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 140Sm 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 140Sm 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 140Sm.

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, 144Sm, is spherical in shape. Adding neutrons to 144Sm changes the deformation to an elongated (prolate) quadrupole shape. The transition from spherical to prolate shape, which occurs for 152Sm 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 140Sm at CERN-ISOLDE found triaxial shape for this isotope, i.e. a shape where all three principal axes of the ellipsoid have different lengths. 140Sm 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 140Sm

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

ISOLDE http://isolde.web.cern.ch and http://isolde.web.cern.ch/sites/isolde.web.cern.ch/files/NuclPhysNew-ISOLDE_0.pdf and 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

3.1.1 Beam production

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

$$\text{p}^+ \text{ (from PSB)} \rightarrow \text{ Production target} \rightarrow \text{GPS} \rightarrow \text{RILIS} \rightarrow \text{REXTRAP?} \rightarrow \text{REXEBIS} \rightarrow \text{HIE-ISOLDE} \rightarrow \text{MINIBALL}$$

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&acdnat=1545216224_d359ddcc40ea1f94369c85 and 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

"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 breader: 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

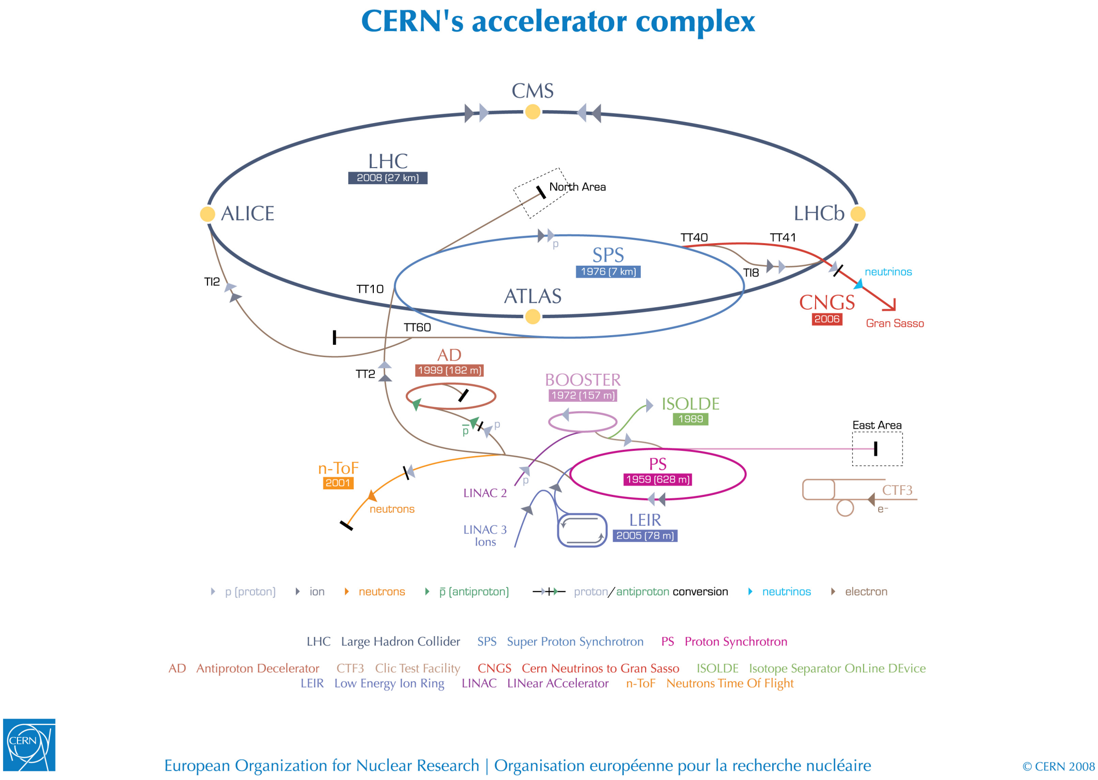


Figure 3.1: The CERN accelerator complex. ISOLDE gets accelerated protons from LINAC 2 and the PS BOOSTER.

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 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

ENSAR2 http://www.ensarfp7.eu

Beam production 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}Pb was chosen as a target. Want high Z so that the probability of excitation is high. Not enough beam energy to excite ^{208}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: $[18.4°, 56.6°]$

3.2.2 γ 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}Sm Coulomb excitation experiment.
Experiment code: IS558
Ta: tantalum (Z = 73)
Sm: samarium (Z = 62)
Pb: lead (Z = 82)

Beam: ^{140}Sm($T_{1/2} \approx 15$ min, 4.65 MeV/u, total 651 MeV), excellent purity
Target: ^{208}Pb(Thickness: 1.4 mg/cm^2)

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

PC:
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): ∼ 40-45 min
AQ4Sort (online calibration): ∼ 120 min

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 is named MiniballCoulexSort and is available on GitHub at https://github.com/Miniball/MiniballCoulexSort. The main steps of using it is outlined in the README.md file.

Data from Miniball comes in the form of .MED-files (Miniball Event Data). In order to analyze this data in ROOT the first part of the sorting is just to convert the MED-files into ROOT-files, and the main file for this is called **MedToRoot.cc**. The process of how to run the

4.2 Scripts

In order to not copy and paste the sorting command in the terminal for every data file, I made a bash script to do this. The script is called **M2R.sh** found in the folder Scripts/sorting on GitHub **(NOT UPLOADED YET)**.

To plot data some scripts had to be written.

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

4.3 Simulation

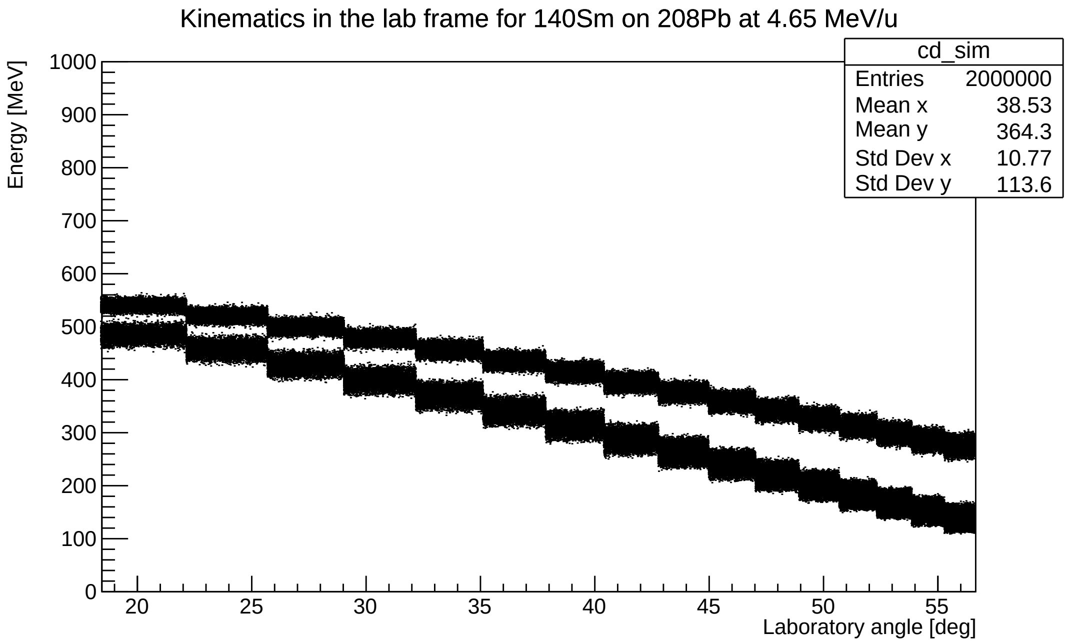
To calibrate the data, we need to know the expected energy of the centroids of the peaks. This was done by simulating the experiment in a program called kinsim3.

kinsim3 is written by Liam Gaffney[1] 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.

[1] Fellow at ISOLDE, affiliated with MINIBALL.

CD to target distance: 26.98 mm.
Simulation done by kinsim3



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: 140Sm on 208Pb:

```
$ 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")
```

similarly for Ni

```
root [2] kinsim3(56, 28, 144, 58, 1.8, 3.395, 0.02, 1.0, 0.6,
    26.98, 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

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 $\Longrightarrow$ 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 γ finder
addback, singles, ...

4.5 Doppler correction

Chapter 5

Experimental results

Chapter 6

Discussion

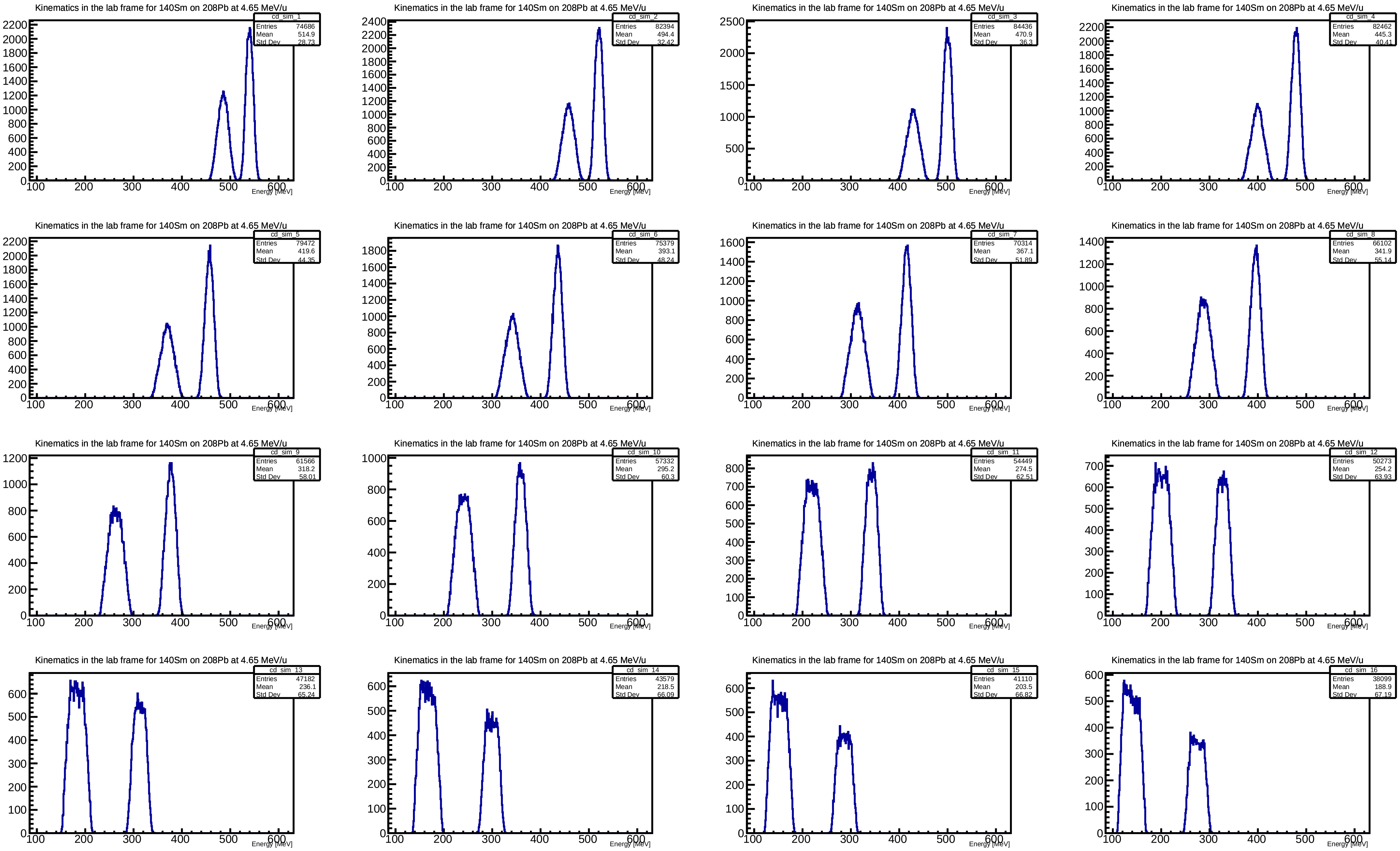
Chapter 7

Summary and outlook

Appendices

Appendix A

Some Appendix



Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_1
Entries 74686
Mean 514.9
Std Dev 28.73
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_2
Entries 82394
Mean 494.4
Std Dev 32.42
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_3
Entries 84436
Mean 470.9
Std Dev 36.3
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_4
Entries 82462
Mean 445.3
Std Dev 40.41
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_5
Entries 79472
Mean 419.6
Std Dev 44.35
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_6
Entries 75379
Mean 393.1
Std Dev 48.24
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_7
Entries 70314
Mean 367.1
Std Dev 51.89
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_8
Entries 66102
Mean 341.9
Std Dev 55.14
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_9
Entries 61566
Mean 318.2
Std Dev 58.01
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_10
Entries 57332
Mean 295.2
Std Dev 60.3
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_11
Entries 54449
Mean 274.5
Std Dev 62.51
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_12
Entries 50273
Mean 254.2
Std Dev 63.93
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_13
Entries 47182
Mean 236.1
Std Dev 65.24
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_14
Entries 43579
Mean 218.5
Std Dev 66.09
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_15
Entries 41110
Mean 203.5
Std Dev 66.82
Kinematics in the lab frame for 140Sm on 208Pb at 4.65 MeV/u
cd_sim_16
Entries 38099
Mean 188.9
Std Dev 67.19
Energy [MeV]

Appendix B

Some other appendix...

Bibliography

[1] E. Clément, M. Zielińska, A. Görgen, et al. Spectroscopic Quadrupole Moments in Sr 96,98: Evidence for Shape Coexistence in Neutron-Rich Strontium Isotopes at N=60. *Physical Review Letters*, 116(2):1–6, 2016. ISSN 10797114. doi: 10.1103/PhysRevLett.116.022701.

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

[3] C. Lefèvre. The CERN accelerator complex. Complexe des accélérateurs du CERN. Dec 2008. URL https://cds.cern.ch/record/1260465.