Cool Title

Project in FYS-3180 at

Oslo Cyclotron Laboratory

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Abstract

abstract abstract

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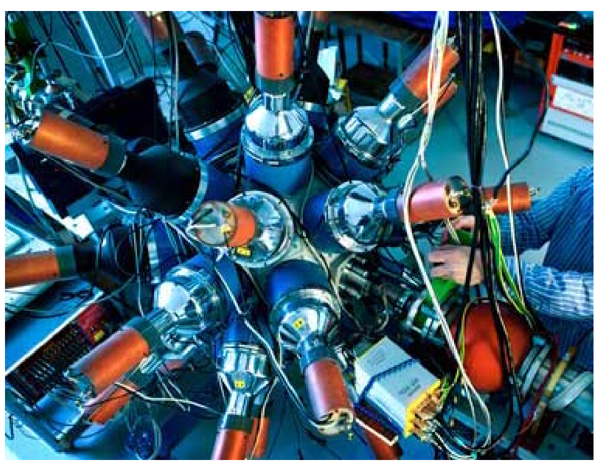

Figure 1: The CACTUS detector in the Oslo Cyclotron Laboratory for the study of particle-γ coincidences. (`//www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/`)

Contents

1 Motivation and purpose

The purpose of this article is to give an (brief) introduction to detectors, systems and methods used in experimental nuclear physics. Important because blablabla learning about how to prepare and conduct an experiment and most importantly analyze and interpret the possible error sources.

Will give an short introduction to the OCL In this project we will focus on the basics of how the cyclotron works and

We will study the raw data from an previous experiment and analyze it as it was the first time to do so.

We will choose a particular reaction and prepare as for a real experiment by calculating (....energy lost in the ...kin...). We will then use data from an earlier experiment, analyse it and discuss possible error sources(?). Will also vertify/compare data with exsisting databases(?).

We will learn the terms: prompt time, particlebananas, thicknessspectra ++ (?)

Goal: particle-gamma coincidence matrix

all source code can be obtained from the OCL websites??

2 Experimental setup and method

The basic consepts of a cyclotron

A cyclotron is a particle accelerator for charged particles. The particles are accelerated with an external electric field and together with a magnetic field the particles are contained in an orbit inside the cyclotron. In nuclear physics a cyclotron is used to accelerate charged particles so that they leave the cyclotron with the desired energy. The goal is then to study nuclear reactions that occur when the particle beam is directed to a target. Two different detectors can then be used to meashure particles and γ-rays that are produced in the reaction.

A simple cyclotron consists of two half -cylinders placed side by side as in figure 2. Every

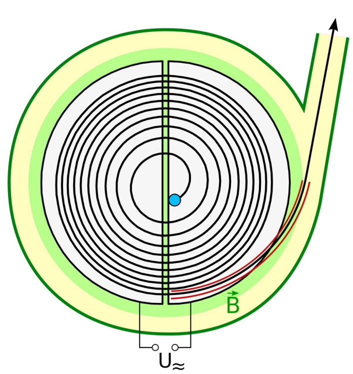

Figure 2: A simple illustration of a cyclotron. The illustration is taken from `http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/ocl-photos/`

time the particles pass between the two cylinders they are accelerated by an oscillating electric field. Therefore the particles increase speed and radius for every half round. Inside the cylinders the electric field is zero, but there is a magnetic field perpendicular to the plane showed in figure 2 that contain the particles in a circular orbit. When the radius of the particle beam is bigger than the radius of the cylinders the particles leave the cyclotron.

2.1 The Oslo Cyclotron laboratory (OCL)

The Oslo Cyclotron Laboratory (OCL) houses the only accelerator in Norway for ionized atoms in basic research[1]. The accelerator is used in various fields of research for instance nuclear physics and nuclear chemistry. Other applications for the Cyclotrone are the production of isotopes for nuclear medicine. The reasearch in nuclear physics at Oslo Cyclotron Laboratory mainly focus on studying the level densities and radiative strength functions where the overall goal is to better understand the atomic nuclei.

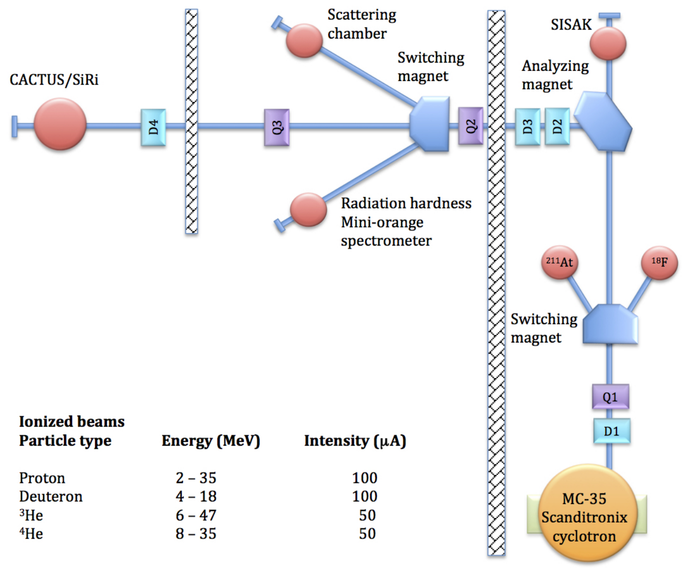

Figure 3: An overview of the Oslo Cyclotron Laboratory with the experimental hall to the right with the cyclotron at the bottom right. The beam line are indicated with a blue line and the target chamber is at the top left (CACTUS/SiRi). The possible beam types, energy and intensity ranges are indicated in the table to bottom left.

An overview of the Oslo Cyclotron Laboratory is given in figure 3. The possible beam types, energy and intensity ranges are indicated in the table to bottom left. In figure 3 we can see the cyclotron vault to the far right with the cyclotron (MC-35 Scanditronix Cyclotron) at the bottom right. The beam of the accelerated particles travels first from the cyclotron along the beam line through a switching magnet and then to a analyzing magnet. The analyzing magnet directs the beam out of the cyclotron vault and into the experimental hall by turning the beam 90 degrees. Then the beam goes through another swiching magnet before hitting the target chamber (CACTUS/SiRi) to the far left in figure 3. Around the target chamber there are two detectors, CACTUS and SiRi. The swiching magnets can also direct the beam to different target stations, but we will only have a closer look at the target chamber associated to the CACTUS and SiRi arrays as this is the target chamber used in the experiment.

2.1.1 The CACTUS and SiRi detectors

The CACTUS/SiRi detector can be used to study particle-gamma coincidences. In figure 4 we see an illustration of a particle from the beam hitting a target nucleus. After the reaction

[1] http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/index.html

a gamma-ray and a particle is emitted in addition to the resulting nucleus beeing changed or excited. We see that the gamma is measured by the CACTUS detector and the emitted particle by the SiRi detector. The figure indicates that the angle between the incident trajectory and the trajectory of the emmitted particle is given as θ.

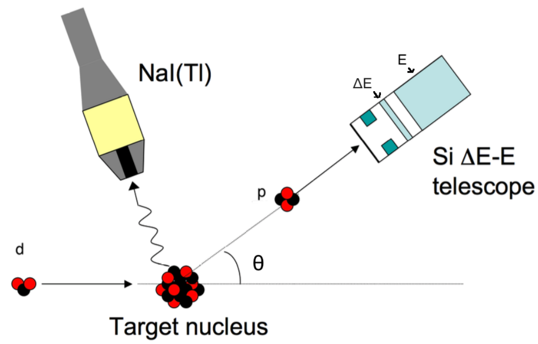

Figure 4: A incident particle hitting a target nucleus. The resulting emmited *gamma*-ray is detected by the CACTUS detectors and the emmitted particle is detected by the SiRi detector. The angle between the incident trajectory and the trajectory of the emmitted particle is given as θ. The two parts of the SiRi detector, 'dE' and 'E' is indicated in the figure.

The CACTUS detector meashures the energies of the γ-rays and counts the number of γ-rays. When looking at the front picture, figure 1, it is not hard to imagine where the CACTUS detector have gotten its name from. The detector consists of 28 NaI scintillation detectors spherically distributed around the target chamber, pointing out like a Cactus. Each of the NaI scintillation detectors meashure the energy of the γ-radiation by using the excitation effect of the incident radiation on a scintillator material (NaI). When the scintillator is excited by radiation it produces a signal that is then converted into an electrical signal that the electronics of the detector processes[2].

The SiRi-array measures the energy of the resulting emitted particle and consists of 8 Silicon detectors on a ring. Each detector is divided into 8 strips which also makes it possible to measure the angle of the particle. The Si detectors uses the properties of a semiconductor, doped Silicon, to meashure the path and energy of the charged particles by detecting the small ionization currents that occur when the charged particles move through the material[3]. In figure 5 we see the Silicon Ring (SiRi) to the left and a illustration of one of the detectors on the right with the induvidual strips marked.

The SiRi detector stops the emmited particle, so it looses all its energy as it moves trough the material. The detector is divided into two parts, one called 'dE' and the other simply 'E'. The first part 'dE' is 130 micrometers thick and this is where the particle looses some ΔE of its energy. In the other part 'E' the particle looses the remaining energy and stops. In addition, an Aluminium foil of 2.8mg/cm^2 thickness is placed before the dE detector. The 'dE' and 'E' positions are indicated in figure 4.

[2]https://en.wikipedia.org/wiki/Scintillation_counter
[3]https://en.wikipedia.org/wiki/Semiconductor_detector

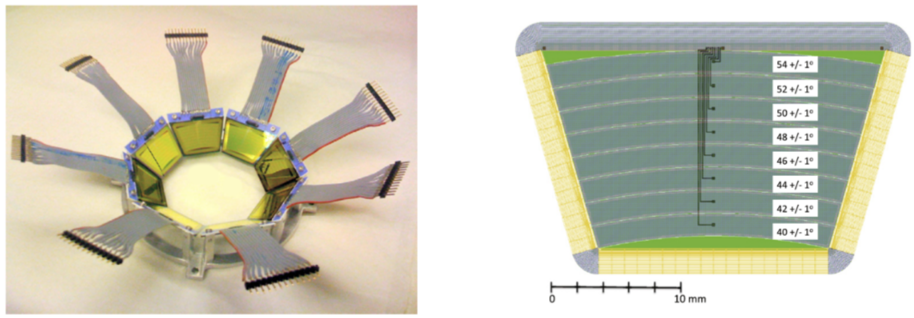

Figure 5: The SiRi detector used to measure the energy of a particle from a particle-gamma coincidence. **Left:** A picture of the Silicon Ring (SiRi). **Right:** A drawing of one of the 8 detectors on the ring with the induvidual strips marked.

2.2 Choice of reaction

In this project we have chosen the reaction $^{28}\mathrm{Si(p, p')}^{28}\mathrm{Si}$ drawn in figure 6. The incident proton will have an energy of 16MeV and the target of ^{2}8Si will have a thickness of $4\mathrm{mg/cm^2}$. We will not performed the experiment, but study raw data from an earlier experiment pretending that we did perform the experiment.

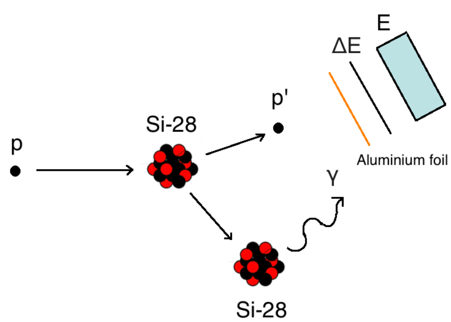

Figure 6: An illustration of the chosen $^{28}\mathrm{Si(p, p')}^{28}\mathrm{Si}$ reaction.

Before conducting the experiment we can study how the proton beam loses energy as it travels through the target and the other materials, until it reaches the E detector with the `OCL SiRi Kinematics Calculator(kin)` software developed by the OCL. This is to make shure that the beam does not have too much energy so it punches through the 'E' detector.

3 Data analysis of the experimental data

The data stored from the experiment are the 'dE' and 'E' signals of the charged particles measured by SiRi and the energy of the γ-rays in coincidence with the charged particles, measured by the CACTUS detector. The data collected with the CACTUS and SiRi detectors are stored in event files; large files with the measured parameter from each event. To extract information from the experiment one have to analyze millions of event files. Luckily the OLC labratory have written a sorting code which does the sorting of the event files. In the process the user can choose to include different features to obtain the final result, a 'clean' coincidence matrix. In the analysis process the following programs have been used:

- `Makefile`: executable file that calls for example `User_sort.cpp` and creates an executable called `sorting`.
- `User_sort.cpp`: the main sorting code in C++. It is possible to modify the code to include time gates, gates on excited nuclear states and so on. It defines what the executable `sorting` will do when it is run.
- `Sorting`: executable file created by the `Makefile`. It uses the batch file when run.
- `Name.batch`: holds information on where to find the data files to be sorted. 'Name' is usually the experiment reaction. The file also includes several parameters and calls the following two programmes:
  - `gainshifts525.dat`: contains information about the calibration of the particle and gamma detectors, together with the time signal calibration.
  - `zrangep.dat`: the range file for the ejected protons. It has information about how the ejected protons lose energy as they penetrate the E dE Si detectors.

The sorting codes can first be run without calibration parameters ('plain') and later with calibration when the parameters are found step by step.

3.1 Particle calibration and bananas

First we have to calibrate the particle detectors, or the SiRi-array. This is done by plotting 'dE' versus 'E', obtaining curves commonly known as 'bananas'. To the left in figure 7 we see the uncalibrated plot of the bananas obtained when the sorting routine is run 'plain'. The bananas are characteristic for each type of ejected particle, there is one banana for each particle. On each banana we can see peaks corresponding to the excited states of the particle.

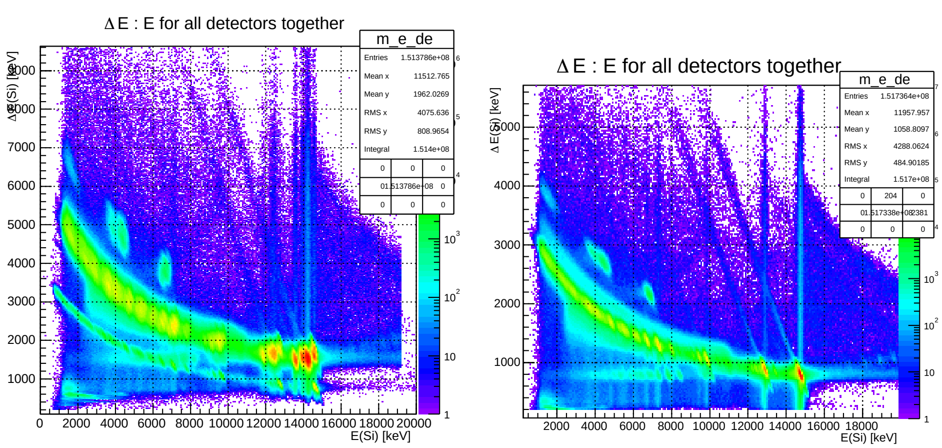

Figure 7: The 'particle bananas', or 'dE' versus 'E' plotted. **Left:** uncalibrated. **Right:** calibrated. Each banana corresponds to one emitted particle. We can also see the peacks corresponding to the excited states of the particle.

The SiRi-array has 8 Silicon detectors, each devided into 8 strips. Theoretically all the bananas should be the same for a given angle. This is not the case experimentally. We correct this experimental effect by aligning all the detectors, or finding the corresponding gain og shift in reference to one detector. We also choose a reference point, for example the energies of the peaks in the bananas corresponding to the ground and first excited states. This reference point can be calculated with the `kin` software.

The response of the detectors should be approximately linear with energy in both ΔE and E meashurements and can be expressed as:

$$E(x) = a_E + b_E x$$
$$\Delta E(x) = a_\Delta + b_\Delta x$$

where x is the channel number, a the shift in the energies and b the gain in the energies. The coefficients a and b are then calculated in such a way that the value $E(x)$ and $\Delta E(x)$ for the reference peaks matches the values calculated with `kin`. This calibration is performed for all the 8 strips and the 8 detectors and then included in the `gain_shift.dat` file. So when the calibration is done the gain-shift file includes the a and b coefficients for both the ΔE and E for each detector.

To the right in figure 7 we see the calibrated bananas obtained when the sorting routine is run with the gain-shift file included. We see that the calibrated plot is much clearer and have sharper excited state peaks than the uncalibrated plot.

3.2 Selecting the data for the ^{28}Si(p,p')^{28}Si reaction

When the particle calibration is done we want to only select the data from the ^{28}Si(p,p')^{28}Si reaction, we need to gate on the banana corresponding to the emitted protons. This is done by using or 'commenting in' the range file `zrangep.dat` in the `.batch`-file. In the left plot in figure 8 we see the aparent thickness of the ΔE detector. The peak is centered at $\approx 130\mu$m which is the actual thickness of the ΔE detector, and the width or range is $\approx 20\mu$m. The range file includes the peak and width read from the left plot in figure 8.

When we use the range file in the `.batch`-file the sorting routine distributes the experimental data around the actual thickness of the ΔE detector. This means that we have gated on the banana that corresponds to the emitted proton or the desired reaction ^{28}Si(p,p')^{28}Si. The selected data can therefore now give us information about the reaction we want to study.

In figure 8 we see the 'banana' plot obtained when running the sorting routine again with the range file. By comparing with the right plot in figure 7 we see that we have selected the banana corresponding to the emitted protons.

After including the range file and sorting again we can find the excitation levels (of the final nucleus?) by projecting the coincidence matrix on the y axis and compare this with other experimental data. In table 1 we see the excited states of ^{28}Si collected from the database of NNDC [4].

In figure 9 we see the coincidence matrix projected on the y axis. Each peak in the plot correspond to an excited state of ^{28}Si. The six first excited stated are marked with a red circle. We see that the values of the excited states marked corresponds well to the values of the energy levels found in table 1. Peaks that do not correspond to a energy level of ^{28}Si is contamination which will be corrected for at a later stage (?).

[4] //www.nndc.bnl.gov/chart/getdataset.jsp?nucleus=28SI&unc=nds

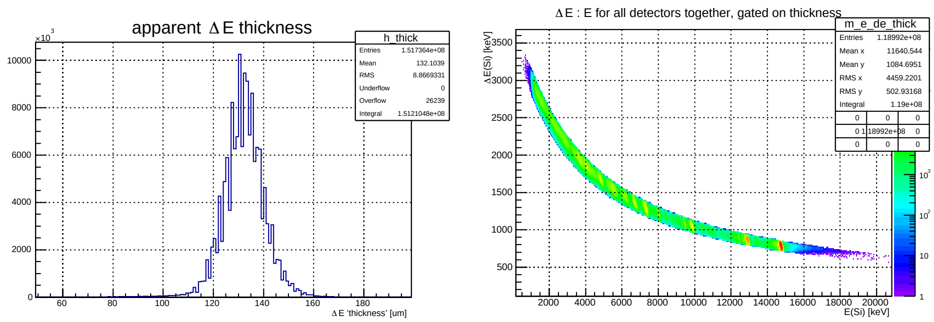

Figure 8: Selecting the data for the ^{28}Si(p,p')^{28}Si reaction. **Left:** The calculated thickness of the ΔE detector. The peak is centered at $\approx 130\mu$m which is the actual thickness of the ΔE detector. Other peaks would have corresponded to other ejected particles. **Right:** The 'banana' plot after particle calibration and gating on one particle banana.

Table 1: The energy levels of ^{28}Si from the Chart of Nuclides found on the NNDC website `//www.nndc.bnl.gov/chart/getdataset.jsp?nucleus=28SI&unc=nds`

E_x [keV]
0
1779.030 11
4617.86 4
4979.92 8
6276.2 7
6690.74 15

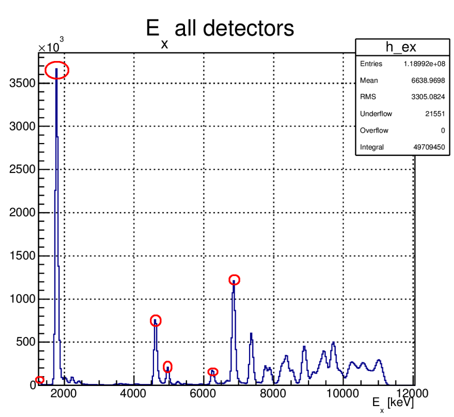

Figure 9: The the coincidence matrix projected on the y axis giving number of counts versus energy, E_x. Each peak corresponds to a excited state of ^{28}Si. The six first excited stated are marked with a red circle to be compared with table 1.

3.3 γ-calibration and treatment of the time signals

We will now look at the procedure used to calibrate the NaI detectors and the time signals. The CACTUS γ detector consists of 28 NaI detectors, and due to differences in the electronics the time signals are not aligned. To correct for this we will use a similar procedure as in section 3.1. We will choose one of the 28 detectors as a reference and read of the peak of (?). We will then use this peak to shift the count(?) peaks for all the other detectors so that all the peaks are aligned. We will also account for the different responce in the detectors, or the gain as in section 3.1.

Finally we have to correct for the fact that the time signal is dependent on the energy, or the amplitude of the signal, also often refered to as the problem of walk'. This problem originates form the use of a spesific type of discriminator. The discriminator gives a time signal, or a count, every time the amplitude are above a certain threshold. This threshold can either be fixed and independent on the signal, or it can be a fraction of the amplitude. The latter are called Constant Fracion Discriminator (CFD) which is the expensive version, and the first are called called Leading Edge Discriminators (LED) which are cheaper. In this experiment we have used LED which gives that the time signal is dependent on the energy.

To correct for the 'problem of walk' we have done a curve fitting to the data of from all the NaI detectors, and coreccted for the energy dependence. In figure 10 we see the uncorrected and corrected plot of the time channels versus the energy of all the NaI detectors.

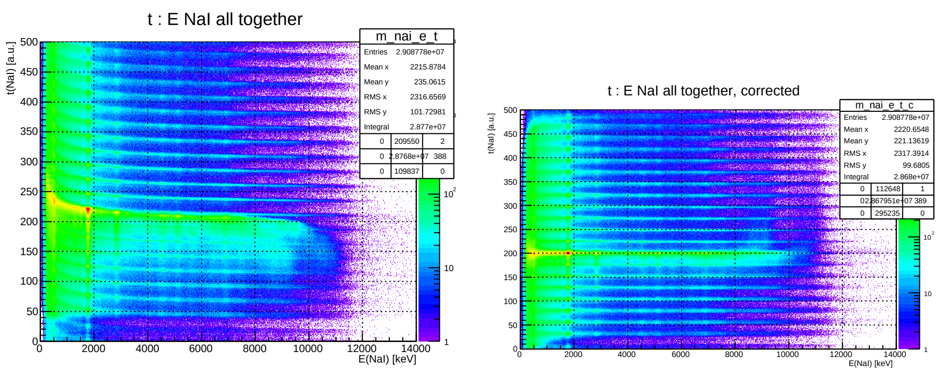

Figure 10: The time channels plotted versus the energy of the all NaI detectors. **Left:** uncalibrated plot with time signals shifted due to LED. **Right:** calibrated plot, corrected whith a curve fitting to the data in the left plot.

When the time signals are corrected we need to gate on the 'prompt gammas'. The 'prompt gammas' are the γ-rays that are in coincidence with the emitted proton. We can gate on the 'prompt gammas' by plotting the aligned time channels versus the number of counts. We then select the a gate around the prompt peak so that we only select the experimental data corresponding to the desired reaction.

But when we measure the γ-rays we might also measure delayed gammas, radiation from a previously excited nucleus that did not instantly decay (form the more stable state) or background. The background is γ-rays from other elements than the target that where excited. We can get rid of the backgrund by doing a measurment without target and then substract this to the experimental data. To get rid of the delayd gammas, or the random coincidences we set a gate on a peak corresponding to the random coincidences and subtract it to the gate on the prompt peak. When this is done we are finished with the γ calibration.

3.4 The coincidence matrix

When the data from the detectors have been corrected we are ready to plot the final goal; the coincidence matrix. In figure 11 we see the coincidence matrix, the plot of the incident energy E_x versus the γ-energy for different stages of the data analysis. The left plot is the coincidence matrix before the detector and time calibration, and the middle plot is after the calibration. To the right we find the final calibrated coincidence matrix with the background substracted. Due to the calibration we can see that the middle plot has clearer peaks than the left plot. All points under the diagonal E_x =E cannot correspond to the reaction because it implies that the incomming energy E_x would be less than the resulting energy E. So it is expected that all the counts below this diagonal disappeares when we substract the background, which we can see is the case in the plot to the right.

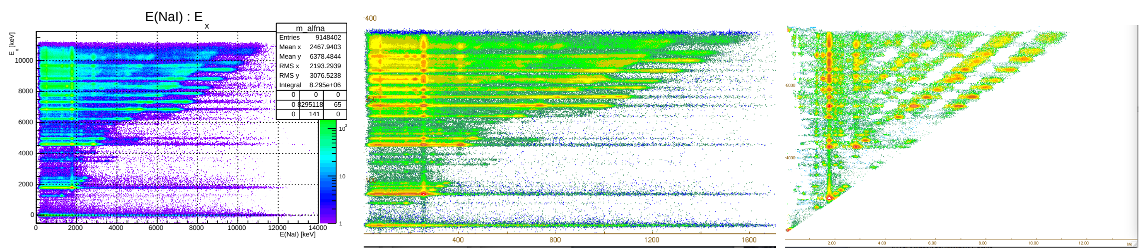

Figure 11: The coincidence matrix (the incident energy E_x versus the γ-energy) plotted for different stages of the data analysis. **Left:** before particle calibration. **Middle:** after particle calibration with background. **Right:** the final coincidence matrix, calibrated and with the background substracted.

4 The Oslo method

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The Oslo method is based on three main steps:

1. Unfolding of the γ-ray spectra
2. Extraction of first-generation γ-rays
3. Extraction of the nuclear level density and the gamma strength function

will look at the first two.

Want this because:

$$P(E_x, E_\gamma) \propto \tau(E_\gamma) \cdot \rho(E_\gamma, E_x)$$

so it is nice to be able to get the first two in one experiment.

4.1 Unfolding of the coincidence matrix

The unfolding procedure corrects for the response of the detectors, or the ways that the γ-rays can interact with the matter in the detector. When the photon with energy E_γ interacts with the detector, we will not see only one peak at the energy E_γ, we will se many peaks corresponding to the possible interactions of the photon with matter.

The γ-rays can interact with matter in the following processes:

1. The photo electric effect
2. Compton scattering
3. Pair reaction (the gamma can produce a electron-positron pair and one or both can escape.

In figure 12 we see an illustration giving a general picture of the peaks produced with the different effects mentioned above. To the far right we see the 'full energy peak' produced by the photo electric effect. Following to lower energies we notice the compton edge before the single escape peak. The single and double escape peaks corresponds to the escape of one or both of the particles in the electron-positron pair positioned 1x and 2x times the electron mass from the full energy peak. The 'backscattering peak' for the lowest possible energy with the compton effect is not included in the figure.

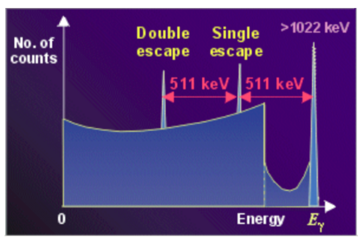

Figure 12: An illustration of the number of counts versus the gamma energy for the three processes. .

It is therefore many processes that contributes to the final γ spectrum. To correct, or unfold the measured gamma spectrum we need to obtain the response matrix $\mathbf{R}$ that contains all the information about the response of the detector. We can express the unfolded gamma spectrum f as:

$$f = \mathbf{Ru}$$

where u is the measured spectrum.

The response $\mathbf{R}$ can be measured, and we assume here that this have already been done. So to obtain the unfolded matrix we simply type a command in the `mama` software developed at OCL.

4.2 Multiplicity and the extraction of the first-generation (primary) γ-rays emitted

In figure 13 we see an illustration of the possible paths a photon can take to the ground state from an excited state. The secondary photons are marked with a red corcle, the primary unmarked. When we count the number of γ-rays with an energy corresponding to a step between two energy levels, we might also count the secondary photons. This will not give us the right picture of the probability to go from one energy level to another. We need a way to separate the different paths taken by the photon, a way to only select the primary photons. This can be done by introducing the multiplicity.

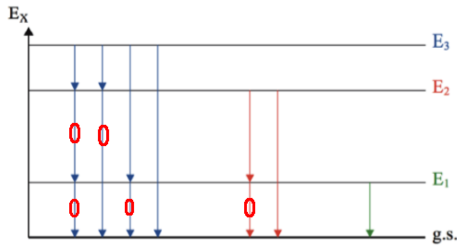

Figure 13: An illustration of the possible paths a photon emitted from an excited state can take to the ground state. The secondary photons are marked with a red corcle, the primary unmarked.

The multiplicity is defined as the average number of γ-rays emitted for a given incident energy E_x. There are at least three methods for obtaining the multiplicity. The average multiplicity can be defined as:

$$\langle M \rangle = \frac{E_x}{\langle E_\gamma \rangle} \tag{1}$$

where $\langle E_\gamma \rangle$ is the mean of the gamma energies. Another definition is:

$$\langle M \rangle = c \cdot \frac{N_c}{N_s} \tag{2}$$

where c is a constant calculated from a energy level for which the multiplicity is known, by for example equation 1. N_c is the coincidence spectre and N_s is the single spectre for a given energy E_x. This is an iterative method also known as the 'first-generation method'.

The next step in the Oslo method would have been to extract the nuclear level density and the strength function.

5 Discussion and Experiences

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