Bremsstrahlung Luminosity Monitoring for SCRIT Project (Report part I)

1 Introduction

In this section the SCRIT research group and the basic ideas of the SCRIT project will be presented. Also this project which is subproject of the SCRIT project will be introduced. ELPH and RIKEN, the two laboratories where I have been doing my studies will also be introduced.
1.1 The SCRIT project

To complete the theory for the properties of the atomic nucleus has been keeping scientists working for over a century now. The discovery of the atomic nucleus made by Ernest Rutherford in the beginning of the 20:th century was ground breaking for a new type of physics, nuclear physics. The properties for the stable nucleus is well known today, but the properties of the short-lived unstable nucleus is still puzzling scientists. The purpose for the SCRIT project is to gather information about size and structure for short-lived unstable nuclei to contribute to a “supermodel” for all nucleus.

To test these properties The SCRIT research group will use electron scattering together with a Self-Containing Radioactive Isotope Target (SCRIT), which is a completely new technique[1,2,3]. The idea is to trap the unstable nuclei in a potential well within an accelerator. While trapped, the electrons in the accelerator will scatter from the nuclei and their momentum will be analyzed with help of a drift chamber. After momentum has been analyzed, the electrons can be identified with help of a plastic scintillator. Energy can be measured with a calorimeter. Some of the energy from the scattering will be released as bremsstrahlung, this will also be detected by a calorimeter and also with a position monitor to determine the luminosity, which leads us to purpose of my sub-project for this larger project.

1.2 This Sub-project

The Bremsstrahlung Luminosity Monitor is a tool that the SCRIT project will use in order to find out the total luminosity. The knowledge of this is essential in order to determine valuable information such as charge density and size of the nuclei of interest. My task is to prepare a position monitor, this monitor will measure the number of electrons and positrons created by the bremsstrahlung and determine at which position they hit the detector. From this information one can determine the fraction of the total luminosity from bremsstrahlung.

1.3 ELPH in Sendai

ELPH is shortage for “Research center for ELection PHoton science” and has been the place were most of my studies have taken place. It is at ELPH I have constructed the position monitor for the project.

1.4 RIKEN in Tokyo

Is the second laboratory where I have been working on the projects. At RIKEN I have been working with installing the detectors in the accelerator hall and testing the detectors with a radioactive source. Read more about RIKEN at http://www.riken.go.jp/engl/

1.5 Divided report

Since this report is made to fit the two courses “Projekt i fysik 30hp” and “Projekt i fysik 15hp” at my home university, Uppsala University, the complete report from the course Individual Research Training in Lab which was taken at Tohoku University will be divided into two reports. The first part (the one you are reading right now) focus on the theoretical explanation, detector testing and circuit setup, while part II focus on software programming and software testing.
2 Method

This section consist of the project plan, the main goal and partial goals of this project.

2.1 Main goal and partial goals

This part consist of the main goals and partial goals of this project. The main goals are the goals that are supposed to be full-filled at the end of the project. The partial goals are goals to be full-filled during the project in order to complete the main goal.

2.1.1 Main goal

The main goal of this sub-project is to build a bremsstrahlung luminosity monitor with associated software for the SCRIT research group’s experiments on electron scattering of short-lived radioactive nucleus.

2.1.2 Partial goals

To complete the main goals the following partial goals have to be completed:

- **Construct bremsstrahlung luminosity monitor (Report part I)**
  To complete this goal I have to gather knowledge in construction of scintillator detectors, Information about the different parts of the detector and the physics behind bremsstrahlung.

- **Software programming (Report part II)**
  To complete the detector system, a software to run the data gathering has to be developed. This will be done in LabVIEW together with FPGA module, since the detector system is suitable for that software development program.

- **Detector testing (Report part I & II)**
  To make sure that the detector system is working properly, a series of tests will be made on cosmic rays, tests with radioactive source will also be made.

- **Software manual writing (Report part II)**
  Write a manual for this detector system so that the system can be used by anyone.

2.2 Project plan

This part consist of the project plan and the time limitations of the project.

2.2.1 Project time and dates

This project will last from October 2010 until August 2011. Notice that the COLABS program ends at the end of the fall semester and the ICI-ECP begins in the spring semester.

2.2.2 Project plan COLABS-program fall semester Oct 2010 - Feb 2011

The project plan of the fall semester is presented in the table below
2010-10-04 to 2010-11-19
Start-up, Work space setup, Theoretical Introduction to nuclear physics
The first thing to in the beginning of the project do is to try to understand the fundamental basics and the theoretical knowledge that is required, especially theory on electron scattering and bremsstrahlung.

2010-11-20 to 2010-12-22
Introduction to detectors, software hardware interface
At this time the work will consist of understanding the main concepts about detector systems and the detector/software interface for this project. If possible, programming of the software will be started here.

2010-12-23 to 2011-01-10
Christmas/New years break

2011-01-11 to 2011-02-22
Construction of detector, software programming
At this time the more practical task start such as constructing the detector system. Programming the software will continue during this period.

2.2.3 Project plan ICI-ECP spring semester May 2011 - Aug 2011
The project plan for the spring semester is presented in the table below

<table>
<thead>
<tr>
<th>Date</th>
<th>Task</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-05-11</td>
<td>Detector system testing</td>
<td>During this period the detector system will be tested and corrections in the software will be made.</td>
</tr>
<tr>
<td>to 2011-07-31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011-07-31</td>
<td>Buffer, finishing project report and software manual</td>
<td>This period is a buffer if there would be problems during the project that will take more time than proposed from the beginning. Software manual will be written during this period.</td>
</tr>
<tr>
<td>to 2011-08-15</td>
<td></td>
<td></td>
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</tbody>
</table>

3 Theory
The underlying theory of the project will be discussed in this section.

3.1 Nuclear Physics background
In 1961, Robert Hofsdater was awarded with the noble prize in physics for his work to understand the atomic nucleus with help of electron scattering. The discoveries that have been made for stable and long-lived radioactive isotopes have shown three important properties.

1. Density saturation
   The charge density is fairly constant within the nucleus.
2. Nuclear radius
   The radius of the nucleus can be described by the following formula:

\[ r = r_0 A^{\frac{1}{3}} \]  

(3.2.1) [4]

Were \( r \) is the radius, \( r_0 \) is a constant and \( A \) is the number of protons and neutrons.

3. Diffuseness
   The diffuseness of the nuclear radius is approximately constant to 2-3 fm.

For short lived RI though, these properties have never been tested, and it has been suggested that these properties are different for some unstable nuclei. With the SCRIT experiment the hope is to determine these properties even for the short-lived nuclei case. How these properties will be determined will be partly explained in the next part.

3.2 Electron Scattering
   Electron scattering is based on the well understood electromagnetic interaction between electrons and the nucleus. The cross section (probability of) electron scattering is:

\[ \frac{d\sigma}{d\Omega} = \sigma_{Mott}|F(q)|^2 \]

(3.2.2) [6]

\( \sigma_{Mott} \) is the Mott cross-section i.e the cross-section for a point like particle, but since the nucleus is not point like, the Mott cross-section has to be multiplied by the form factor \( F(q) \). The mott cross-section can be explained by this formula:

\[ \sigma_{Mott} = \left( \frac{\alpha z^2 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} \right) \]

(3.2.3) [6]

Here \( z \) is the atomic number of the nucleus, \( \alpha \) is the fine structure constant which is approximately 1/137, \( E \) is the electron energy and \( \theta \) is the scattered angle. The form factor is the Fourier transform of the charge distribution that can be explained by the following formula:

\[ F(q) = \int e^{-iq \cdot r} \rho(r) dr \]

(3.2.4) [7]

\( \rho \) is the charge density and \( q \) is the electron momentum transfer:

\[ q = k_i - k_f \]

(3.2.5) [7]
where $k$ is the electron momentum, initially and after the collision. The momentum transfer $q$ is also be expressed by following formula:

$$|q| = 2E \sin(\theta / 2).$$  
(3.2.6) [7]

So in principle $q$ can be expressed as a function of $\theta$. If the form factor formula is inverse transformed, the charge distribution can be obtained:

$$\rho(\mathbf{r}) = \int e^{-i \mathbf{q} \cdot \mathbf{r}} F(\mathbf{q}) d\mathbf{q}.$$  
(3.2.7) [7]

So, if total cross-section and the momentum vector can be determined by experimental methods, the charged distribution can be determined. Which is actually the case for the SCRIT experiment. The momentum vector can be determined with a combination of a spectrometer and drift chambers. The cross-section can be determined from the following formula:

$$\frac{dN}{d\Omega} = L \frac{d\sigma}{d\Omega}.$$  
(3.2.8) [8]

Where the term on the left side of the equal sign is the counting rate and $L$ is the luminosity. By measuring electron spectrum with a calorimeter it is possible to determine the counting rate. But to determine the electron scattering cross section, the luminosity has to be determined, this can be done by measuring bremsstrahlung.

### 3.2 Bremsstrahlung

Electrons can lose energy when interacting with nuclei in two ways, by collision and by radiation. The energy loss due to radiation can be described by:

$$- \left( \frac{dE}{dx} \right)_{rad} = N \int_0^{E_{\gamma 0}} E_\gamma \frac{d\sigma}{dE_\gamma} (E_{\gamma 0}, E_\gamma) dE_\gamma.$$  
(3.3.1) [8]

Where $N$ is the atomic density, $E_\gamma$ is the bremsstrahlung photon, $\sigma$ is the cross-section and $E_{\gamma 0}$ is the initial electron energy. The cross-section can be described by the following function:

$$d\sigma = 4 \pi r_e^2 2 \alpha \frac{dE_\gamma}{E_\gamma} \left\{ (1 + e^2) [\frac{\theta_1}{4} - (\ln Z)/3 - f(Z)] - 2 e^{\frac{\theta_1}{4}} - (\ln Z)/3 - f(Z)]/3 \right\}.$$  
(3.3.2) [8]
Here, $Z$ is the atomic number, $r_e$ is the classic electron radius, $\alpha$ is $1/137$, $\varepsilon$ is the ratio of the final electron energy and initial electron energy. The two $\phi$ functions are screening functions depending on $\xi$ which is the quantity that describes the effect of screening. $f(Z)$ is the Coulomb correction. This $\sigma$ value gives information of the cross section for a specific energy of the gamma ray. If this function is integrated over different energies, one obtains the total cross section for bremsstrahlung.

Figure 3.2.1 Graph of the bremsstrahlung differential cross-section vs. the photon energy. In this case the electron energy has been set to 150MeV.
To determine the bremsstrahlung energy a Lead-glass Cherenkov detector will be used. If all the bremsstrahlung can be detected in the experiment the total luminosity can be determined. But since bremsstrahlung is not emitted in a straight line when electrons lose energy as radiation in interaction with RI target, it is also needed to determine how big fraction of the bremsstrahlung that hit the calorimeter, to do this a position monitor is needed. The spreading of the bremsstrahlung can be determined by the following formula:

$$\sigma(k, x) dkd\sigma = \frac{1}{12} \left( \frac{Z^2}{m^2} \right)^2 \frac{2}{x} d\sigma [9]$$

and

$$\frac{1}{M(x)} = \left( \frac{\mu k}{2 E_0 E} \right)^2 + \left( \frac{Z^{1/2}}{C(x^2 + 1)} \right)^2$$

(3.3.4) [9]

Here $E_0$ is the initial energy of the electron, $E$ is the energy of the scattered electron $Z$ is atomic number, $m$ is the mass of the electron $k$ is the energy difference of the scattered electron and the initial energy, $\mu$ is the rest mass of the electron $C$ is a constant and the value is 111, $e$ is the electron charge and $x$ is the reduced angle which is:

$$x = E_0 \theta_0 / \mu.$$
where $\theta_0$ is the angle between the $\gamma$ and the incident electron.

The cross-section angular dependence gives us information of how the gamma rays will be distributed geometrically. And when plotting cross-section vs. the angle one obtains a Gaussian distribution. The shape of the Gaussian function will change depending on the photon energy. And if one would integrate over all energies and angles one will get the total cross section i.e equation (3.3.2) integrated for all photon energies.

For the detector to detect the bremsstrahlung, it is only possible to measure some part of the bremsstrahlung. With the position monitor it will be possible to determine the fraction of the total bremsstrahlung that is detected by the calorimeter. By combining the position monitor with the calorimeter the total luminosity can be determined. The total luminosity can then be used to calculate the cross-section for electron scattering. with equation (3.2.8)

The SCRIT chamber is about 6.7m upstream from the detector. In front of the detector we have placed a collimator that has a radius of 25mm. If we divide by distance we get the maximum angle for the detector to detect i.e 3.8mrad, this angle is shown in figure 3.2.3.
4. Hardware and Support

In this section the hardware will be described, also the design of hardware and support will be shown.

4.1 Hardware

The detectors are a Bicron BFC-10 plastic scintillator detectors, which have been constructed by Saint-Gobain Crystals and designed by Suda Toshimi. More specifications can be found at the Saint-Gobain detectors homepage [10]. The photomultipliers that is used together with the detectors are Hamamatsu H6568 photomultipliers. More specifications can be found in at the Hamamatsu homepage [11]. The FPGA that have been used is a National instruments PXI-81069 together with a Ni PXI 1031 computer and a NI PXI-7841R DAQ system. Further information about this two units can be found on national instruments homepage[12].

Figure 3.2.4 A picture of the accelerator and luminosity monitor (red circle). In the upper middle part of the accelerator it is also possible to see the SCRIT chamber, drift chamber and calorimeter.
4.2 Support

The Bremsstrahlung luminosity monitor is placed in a special designed support for this purpose. The support is designed to hold the both of the 16 channel fiber detector sets and two trigger detectors. There is also a height adjust support that can adjust the height of the box so that the main support can be placed in the beam center. Figure 5.2.1 hows a schematic sketch of the main support box, Figure 5.2.2 shows a sketch of the height adjustment support and Figure 5.2.3 shows a photo of both the supports in place at RIKEN.

Figure 4.2.1 This picture shows a schematic sketch of the detector setup with support, the box size is 200x500x500 mm and the support it is standing on is 350 x 500 mm
4.2.2 This picture shows a schematic sketch of the height adjustment support. The construction is based on two aluminium plates with holes so that height can be adjusted with nuts. The area of the upper plate is 350x500 mm and the lower plate is 450x500 mm.

4.2.3 Detector support and height support in position at RIKEN

5 Circuits

In this part the bremsstrahlung luminosity monitor circuit and other test circuits will be explained.

5.1 Circuit to measure ADC spectrum

In order to make good discrimination i.e to filter noise, it is necessary to measure energy (ADC) spectrum.
When particle is detected at the fiber detector, the signal will be sent to a linear fan in/out to duplicate the signal so that it can be sent to both the ADC and and the discriminator. At the discriminator the signal will be manipulated to a logical NIM signal. The logical signal will be sent to a coincidence module, where coincidence with a trigger detector will be taken, this is done so that it is sure that the detector fires because of a beta particle, that will be used to test the energy spectrum of the fiber detectors. If there is coincidence between the fiber detector and the trigger detector, the signal will be sent to a gate generator where the signal will be manipulated so that the pulse is long and delayed enough to make a gate signal. The gate signal is sent to a logic fan in/out to duplicate the signal. The gate signal is now sent to the ADC, an interrupt register and another gate generator. ADC mean “Analogue to Digital Converter”. The signal from the fiber detector will be sent here with some delay, so that when the gate is open i.e when there is coincidence between the fiber and the trigger detector, the analogue signal from the detector will be converted to digital data. The gate signal will also be sent to an interrupt register that will tell the UNIX computer to register data, when UNIX computer have registered data, it will send a signal through the output register to the other gate generator. This gate generator have already got a gate signal from the first gate generator, this is done so that the second gate generator can make veto signal. The veto signal is also a logical signal that is starts when a signal comes from first gate generator and stops when it receive signal from output register. The veto makes it not possible for the first gate generator to generate any gate signals as long as the veto signal is on.

5.2 Position monitor circuit

The position monitor is the circuit that is going to be used for the SCRIT experiment. With this circuit the spatial distribution of electron/positron pairs generated by bremsstrahlung is measured.
Figure 5.2.1 flow chart of position monitor setup

The position monitor consist of 32 individual detectors that is combined in a detector grid consisting of 256 detection points where electron/positron pairs can be detected. When a particle is detected an analogue signal is sent to a discriminator that transforms the signal in to a logical NIM signal. Then coincidence is taken with two trigger detectors. The pulse is then sent to a gate generator that will extend the pulse width in order to make the pulse suitable for the FPGA DAQ (see chap 6.1). The NIM signal will then be transformed into a TTL signal in a NIM2TTL module, afterwards it is sent to the FPGA and then it can be handled by FPGA DAQ software. The detector software will be explained in part II of the report.

6 Detector tests

The detector tests have been carried out during the spring semester in RIKEN, Tokyo. During all experiments the voltage to the photo multipliers have been set to 950V. The discriminator threshold was set to the following values with help of the test that is described in chap 7.1:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Discriminator threshold for X detectors</th>
<th>Discriminator threshold for Y detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130mV*</td>
<td>83mV</td>
</tr>
<tr>
<td>2</td>
<td>105mV</td>
<td>83mV</td>
</tr>
<tr>
<td>3</td>
<td>105mV</td>
<td>83mV</td>
</tr>
<tr>
<td>4</td>
<td>100mV</td>
<td>83mV</td>
</tr>
<tr>
<td>5</td>
<td>100mV</td>
<td>83mV</td>
</tr>
<tr>
<td>6</td>
<td>115mV*</td>
<td>83mV</td>
</tr>
<tr>
<td>7</td>
<td>100mV</td>
<td>83mV</td>
</tr>
<tr>
<td>8</td>
<td>100mV</td>
<td>83mV</td>
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<td>---</td>
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</tr>
<tr>
<td>9</td>
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<tr>
<td>10</td>
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<td>13</td>
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<tr>
<td>14</td>
<td>120mV</td>
<td>83mV</td>
</tr>
<tr>
<td>15</td>
<td>101mV</td>
<td>83mV</td>
</tr>
<tr>
<td>16</td>
<td>95mV</td>
<td>83mV</td>
</tr>
</tbody>
</table>

*There has been some problems with these channels. The channel for the first detector has not been working at all during the last experiment and was therefore changed to another discriminator. The discriminator value for the channel corresponding to the 6:th X-detector has not been stable. Make sure that the value is not to low before use.

### 6.1 Detector response and discriminator threshold set

To be sure that a detector can measure all particles that goes through it, it is essential to set the discriminator level so that you are sure that minimum ionizing particle (MIP) is measured. This is the minimum energy that the particle will lose when traveling through the detector. Particles lose energy in a thin absorber with the probability of the landau distribution.

*Figure 7.1.1 This figure shows an example of how the landau distribution can look like and the blue arrow shows where the level of MIP is.*

To make this experiment the circuit from chap 5.1 was used. To determine the MIP and threshold
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level for the discriminators a beta source $^{90}$Sr was used. The software that was used for DAQ for this experiment was not the FPGA DAQ since this circuit is connected to a CAMAC system that is controlled by a UNIX based program. To plot the energy spectrum a program called PAW was used. Read more about PAW on [http://wwwasd.web.cern.ch/wwwasd/paw/](http://wwwasd.web.cern.ch/wwwasd/paw/). The energy spectrum from these measurements have been placed in Appendix A.

7 Summary

The position monitor has now been installed in RIKEN at the accelerator together with support and trigger detectors. The detector and testings shows that the detectors are working properly and are ready to use for luminosity measurements at SCRIT experiment.

References

<table>
<thead>
<tr>
<th>[number]</th>
<th>Source name</th>
<th>Type of source</th>
<th>Acces (e.g, homepage, ISBN)</th>
<th>Date</th>
</tr>
</thead>
</table>
Appendix (Individual fiber spectrum)

In this appendix the ADC spectrum for each fiber detector will be presented. If compared to figure 7.1.1 it is clear to see that all detector are fully capable of detecting MIP. The discriminator threshold level has been set close to this level for each detector.

Y detectors 1-16:
Y1 (the arrow shows approximately where the discriminator threshold has been set, the position is for all detectors)
X detectors 1-16
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