AN UPGRADE OF THE SCANDAL FACILITY FOR NEUTRON SCATTERING MEASUREMENTS AT 175 MEV

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Abstract

The experimental setup SCANDAL, used for measurements of the differential cross section for elastic neutron scattering, has been upgraded with new Na doped CsI scintillating detectors for measurements at 175 MeV. Two experimental campaigns have been carried out, collecting data on three different nuclei: iron, bismuth and silicon. SCANDAL has also been used in an attempt to measure the proton content in ANITA, the white neutron beam at the The Svedberg Laboratory in Uppsala. This thesis describes the design of the new SCANDAL, and the details of the first experiment. Some of the characteristics of the new setup, such as energy resolution, are illustrated by the early steps in the analysis of the first experimental data, collected in January and February 2009.
Included papers:

Paper 1
An upgrade of the SCANDAL facility for neutron scattering measurements at 175 MeV


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1. Introduction

The work described in this thesis started in the spring of 2007. SCANDAL [1], an experimental setup used for measurements of the differential cross section for elastic neutron scattering, was to be upgraded with new CsI scintillating detectors for measurements at higher energies than before. Since then, two experimental campaigns have been carried out, collecting data on three different nuclei: iron, bismuth, and silicon. SCANDAL has also been used in an attempt to measure the proton content in ANITA [2], the white neutron beam at the The Svedberg Laboratory (TSL) [3]. My work as a PhD student has been to design and install these new detectors on SCANDAL, run experiments and analyze the acquired data.

Collecting nuclear data of this kind is motivated both by various applications and an improved understanding of fundamental physics. There is a shortage of neutron-induced experimental data today in the 20 - 200 MeV region (for a full review of existing data sets, see ref. [4]). Filling this gap will help improve the theoretical models of nuclear reactions. In particular the optical model potential (OMP) [5] would benefit from elastic scattering data. The OMP is a key ingredient in nuclear reaction codes, widely used in many applications. We find three major fields of applications involving neutrons at these energies. In radiation treatment of cancer tumors, neutron therapy has proven to be a good alternative in some cases where conventional radiation treatment, using photons or electrons, has failed [6]. Neutron data is therefore needed to improve our understanding of the dose delivery to the human body.

In electronic devices, especially at high altitudes, e.g. in airplanes, cosmic-ray neutrons can induce a nuclear reaction in the silicon substrate, and thereby cause a random change of the memory content. This is obviously unwanted and the problem is referred to as single-event-effects [7]. Nuclear data on elastic neutron scattering is very useful in this field of research, since the elastic scattering cross section makes up the larger part of the total neutron cross section [8]. Electronics testing related to this is routinely carried out at the neutron beam facility at TSL [9].

The third, and maybe the most obvious, field of application for this type of nuclear data is nuclear technology for energy purposes – nuclear power. Nuclear reactors of today produce radioactive waste, which is difficult to handle. Future reactor concepts, e.g. accelerator driven systems (ADS), may be a solution to this problem. Cross sections of elastic neutron scattering on H, D, C, O, Fe, Y, and Pb, at 96 MeV, have previously been measured at TSL in Uppsala, using the experimental setup SCANDAL, see e.g. [10], [11]. The results show good agreement with theoretical predictions. From some of these data sets, namely C, Fe, Y and Pb, information on inelastic scattering has also been extracted [12]. The new detectors on SCANDAL are designed for measurements of elastic, and possibly inelastic, scattering at 175 MeV, which is the maximum neutron energy available at TSL. This thesis describes the design of the new SCANDAL, and the details of the first experiment. Some of the characteristics of the new setup, such as energy resolution, are illustrated by the early steps in the analysis of the experimental data. But first, some theoretical background to neutron scattering.

2. Elastic neutron scattering and the optical model potential

The angular distribution of neutrons scattered off a nucleus resembles the diffraction pattern of light scattered by an opaque circular disc. It has alternating minima and maxima, at a spacing depending on the wavelength of the scattered particle. For neutrons scattered off a nucleus the intensity at the minima never reaches zero, as it does in the case of light scattered by a disc. The distribution seems to be smeared out, why the nucleus is sometimes described as having fuzzy edges. This fuzziness is in theoretical nuclear physics translated into a potential, with which the incoming neutron interacts.
The shape of the angular distribution, or the differential cross section, of neutrons elastically scattered on iron at 96 MeV can be seen in figure 1. The top solid line is a simulation made using the software TALYS [13], and the diamonds are SCANDAL data [10], previously measured at TSL. The bottom dashed line is a simulation of neutron scattering on iron at 175 MeV, the energy of the present experiments. It shows what we expect to measure with the new SCANDAL setup.

Figure 1: The differential cross section of elastic neutron scattering on $^{56}$Fe. The top solid line is a simulation made using the software TALYS, and the diamonds are SCANDAL data. The bottom dashed line is a simulation of neutron scattering on iron at 175 MeV, and it shows what we expect to measure with new SCANDAL setup.

For normalization of SCANDAL data we use the simple relation that the total cross section for neutrons consists of the reaction cross section, the elastic scattering cross section and the inelastic scattering cross section. The total cross section and the reaction cross section are well known for many nuclei at a wide range of energies. The inelastic scattering cross section is very small compared to the elastic scattering cross section, and a small correction is sufficient. This way of normalizing affects the choice of target nuclei for the experiments. If the total cross section and the reaction cross section are not known, the SCANDAL data cannot be normalized.

It would be impossible to measure the cross section of all different reactions, on all nuclei, for all different energies. These measurements are both expensive and time consuming. Cross sections are therefore often calculated instead, using theoretical models based on the optical model potential (OMP) [5]. The OMP describes the interaction between a nucleon and a nucleus. The possibility for a nucleon to be absorbed, and thereby “disappear”, is represented by an imaginary part in this potential. This idea was borrowed from optics, and that is why it is called the optical model potential.

There are two different approaches to determining the OMP, the theoretical and the phenomenological. In the former, sometimes called the microscopic optical potential, the potential is established theoretically. In the latter, the parameters of a physically reasonable form of the potential are adjusted by fits to experimental data. This is
where our experiments enter the picture. By measuring some reactions, on some nuclei, at some energies, the models can be improved and a global optical potential can be established.

3. Experimental facilities and procedures

3.1 The neutron beam facility at TSL

A schematic figure of the neutron beam facility at TSL can be seen in figure 2. The facility is described in detail in ref. [3]. Protons from the cyclotron hit a lithium target and produce a quasi mono-energetic neutron beam. The reaction employed is $^7\text{Li} (p, n)^7\text{Be}$. TSL can deliver a neutron beam in the energy range 11 – 175 MeV. After the lithium target, the protons in the beam are deflected by a magnet, into a well shielded proton beam dump 10 meters away. The neutron beam continues through a set of iron collimators into the experimental hall, which is on the other side of an iron wall. After recent changes at TSL, where the lithium target was moved closer to the experimental area to increase the neutron intensity of the beam [3], both SCANDAL and the experimental setup Medley [14] have suffered from increased background radiation. Since 2008, an additional iron wall can be erected between the neutron production target and the experimental area for additional background shielding. This wall was used during the experiments described here.

Figure 2: A schematic view of the neutron beam facility at TSL. The experimental setups Medley and SCANDAL can be seen in the experimental area. The installation of the iron wall has forced SCANDAL 87 cm farther downstream, and the pivot point is now at 727 cm from the lithium target.

SCANDAL experiments are often run in parallel with Medley, that measures light ion production. In these cases, Medley is positioned upstream of SCANDAL. The Medley vacuum is terminated by a 0.1 mm thin stainless steel window, see figure 3, and the targets used are typical less than 0.5 mm thick.

The pivot point of SCANDAL is 727 cm downstream from the lithium target. About 9 meters further down the line

![Diagram of the neutron beam facility at TSL](image-url)
is the neutron beam dump. For monitoring of the neutron flux there is a thin film breakdown counter \[15\] and an ionization chamber monitor in the neutron beam and a Faraday cup at the proton beam dump. The energy spectrum for the quasi mono-energetic neutron beam has a full energy peak, containing about 40 % of the neutrons, and a low energy tail \[3\]. In the analysis of the SCANDAL data, the low energy neutrons can be suppressed using time-of-flight techniques, where the radio frequency from the cyclotron serves as a time reference. This is particularly important if data on inelastic scattering is to be analyzed. The user at TSL can chose between different collimator sets. For SCANDAL and Medley runs, conical collimators following a cylindrical part with a defining diameter of 2 cm, are usually used, which gives a beam diameter of 8.2 cm at the SCANDAL target.

### 3.2 SCANDAL

#### 3.2.1. Overview

SCANDAL has previously been described in great detail, e.g. \[1\]. A schematic picture of the setup can be seen in figure 3. The scattering target is placed on a table in front of the two identical SCANDAL arms. Each arm can be swung into the desired angle, together typically covering angles between 10° and 70° in the lab system. The arms are usually put in such a way that their angular range have a slight overlap, to get a cross check of systematical errors between the two arms. It is also desirable to put one of the arms as close to the beam as possible, to measure at small angles. This is important for normalization of the measured cross section, since the scattering cross section peaks at forward angles. The limiting factor of how close to the beam we can get is the housing of the CsI detectors, since any material in the beam will cause an unwanted background of scattered particles. The SCANDAL arms are flexible enough to be turned all the way around for measurements beyond 90°.

SCANDAL detects recoil protons from hydrogen in a plastic scintillator, rather than the original scattered neutrons. When a neutron has been scattered by the target, it passes through the veto scintillator, which is a 2 mm thick plastic scintillator, 60 cm wide and 30 cm high. Its chemical composition is C\(_1\)H\(_{1.1}\). A neutron passing through will not give a signal in this detector, but any charged particles will. The veto scintillator serves to reject charged particles produced in the target, by acting as a fast veto on the trigger signal for the data acquisition system. The second detector is the active converter, where the neutron is converted into a proton in the reaction H (n, p). It is a 20 mm thick plastic scintillator of the same material as the previous one, 60 cm wide and 30 cm high, and it measures the energy loss of the recoil proton in the converter material. Since the energy loss can be compensated for when using an active converter, it is possible to use a thicker converter without impairing the energy resolution. A thicker converter means a larger volume of material, and hence more conversions.

The angle of the outgoing particle may change relative to the incoming particle in the conversion. Therefore two drift chambers \[16\] record the path of the outgoing proton. The proton path determines the conversion point, and the scattering angle of the original neutron can be calculated. However, conversion on carbon might also occur in the plastic of the converter scintillator. But as this reaction has a Q-value of -12.6 MeV, protons scattered on H at angles smaller than 15° can be identified on basis of their energy. Protons scattered on H at larger angles than 15° on the other hand, will lose more than 12.6 MeV due to kinematics, and cannot be distinguished from protons produced on carbon. In the analysis, the drift chamber information can be used to discard all events with a conversion angle above 15°.

A 2 mm thick plastic scintillator, 60 cm wide and 30 cm high, is placed in front of the drift chambers, and a 2 mm thick plastic scintillator, 75 cm wide and 30 cm high, is placed behind them. Coincident signals from these two
define a trigger criterion for the data acquisition. The very last detector, at the back of the SCANDAL arms, is an array of CsI crystals (these are described in detail in section 3.2.3). They measure the full energy of the protons, which is necessary for distinguishing between protons originating from elastically scattered neutrons, and protons originating from inelastically scattered neutrons. The energy losses in the plastic scintillators are recorded, and the total energy can be corrected for these losses event by event.

Figure 3: A schematic figure of the SCANDAL setup. The neutron beam leaves the Medley setup, at the bottom of the picture, and passes through the multi-target box and the scattering target on the table. It continues through parts of the right SCANDAL arm, which have been designed to allow measurements at small angles close to the beam, but with as little material as possible in the beam. The scattered neutrons are detected by conversion to protons. A typical event is illustrated by a neutron and a proton path.
SCANDAL can be operated in both neutron mode and proton mode. If the signal from the veto scintillator is used as a veto in the data acquisition trigger, only neutrons will be recorded. If we instead require a triple coincidence between the veto, trigger one and trigger two scintillators, then only charged particles will be recorded. Protons can be distinguished from other charged particles in the off-line analysis using $dE$-$E$ techniques, see section 4.2. Proton mode is used for energy calibration of the detectors, see section 3.3.1.

An optional feature of SCANDAL is the multi-target box, which sits upstream of the position of the scattering target, see figure 3. It is mainly used for calibration purposes, but can, if left empty, also be used for rejection of charged particles in the neutron beam during cross section measurements. The rejection of charged particles is then done in the off-line analysis. Seven different scattering targets can be placed in the multi-target box at the same time. The target planes are separated by multi-wire proportional counters, which means that for $(n, p)$ reactions the scattering plane for each event can be identified. A more detailed description of the multi-target box is given in ref. [17].

The detection efficiency of SCANDAL varies with the neutron beam energy because of varying reaction cross sections. Typically, cross sections are smaller for higher energies, which gives a lower detection efficiency. The neutron detection efficiency consists of two parts: the conversion efficiency and the proton detection efficiency. The conversion efficiency depends on the $(n, p)$ cross section for hydrogen, the converter thickness and the accepted conversion angle. For 175 MeV neutrons, a 20 mm thick converter and an accepted conversion angle of 15°, it is $6.1 \times 10^{-4}$.

The proton detection efficiency consists of many parts: the efficiency of the drift chamber planes, correct drift chamber wire selection in the analysis in case of double hits and the CsI response. The efficiency of the drift chamber planes is assumed to be the same at 175 MeV as at 96 MeV. It has been estimated to be 0.93 for each drift chamber plane [1]. The total contribution from the four planes is thus 0.75. The analysis of the data will show how common double hits are, but previous experience shows that the contribution to the detection efficiency is about 0.93 from the wire selection process.

The CsI full energy deposition efficiency is estimated to be 0.83 at 175 MeV. This is based on an investigation of CsI(Tl) detectors [18], previously carried out at the same beam line at TSL. This points towards a proton detection efficiency of about 0.6 at 175 MeV. The neutron detection efficiency is therefore estimated to be $3.6 \times 10^{-4}$. For estimation of the count rate in the experiment, the dead time of the data acquisition system and neutron reaction losses in the target have to be taken into account as well. The reaction losses in the 11 cm diameter Fe target are estimated to be about 20%.

The angular resolution achieved in SCANDAL depends on the size of the scattering target and the beam diameter. It will be worse at higher energies, because we have to use larger targets and beam size, once again because of smaller cross sections at higher energies. Using a target of about 11 cm in diameter, as in the present measurements, and a beam diameter of 8.2 cm, the angular resolution is about 2.3° (rms).

The old SCANDAL setup had a total energy resolution of 3.7 MeV, to which the CsI detectors contributed 3.0 MeV [1]. A similar number is expected in the new setup. There are four contributions to the energy resolution: the energy distribution in the neutron beam, straggling in the plastic scintillators, straggling in other materials and the resolution of the CsI detectors. The first three of these contributions are 2.5 MeV, 1.9 MeV and 1.1 MeV respectively in the new SCANDAL. The estimations of the contributions from straggling in different materials are based on calculations of stopping ranges calculated using the SRIM software [19]. It is reasonable to expect the energy resolution in the CsI detectors to be roughly proportional to the square root of the energy. Assuming that the new CsI detectors behave in a similar way to the old ones, a resolution of 4.1 MeV can be expected for the new detectors at 175 MeV. This would mean a total resolution of 5.3 MeV for the new setup.
As a worst-case scenario, if the energy dependence of the resolution is linear, the energy resolution of the CsI detectors can be 5.5 MeV. For the new setup this would result in a total energy resolution of 6.4 MeV at 175 MeV. The actual measured energy resolution is discussed in section 5.

3.2.2 The new SCANDAL

The origin of this project was a wish to measure elastic neutron scattering at higher energies than before, i.e. 175 MeV. At higher energies, the cross sections are typically smaller. This makes the experiments more time consuming and a weaker signal makes the experiment more sensitive to the background conditions. Particles of higher energy also require more detector material for energy measurements, and that is why SCANDAL needed an upgrade. But there was one more reason why we wanted new CsI detectors. The CsI crystals of the old SCANDAL setup were originally not designed for SCANDAL. Their shape was therefore not optimal for the task [1]. Their conical shape made the data analysis somewhat complicated, and caused a loss in the statistics because their full volume could not be used. SCANDAL has now been upgraded with larger, and more suitably shaped, Na-doped CsI crystals and PM-tubes, see figure 4. The right angles of the crystal walls in the new detector design mean that any corrections, concerning hit position within the crystal, which might have to be applied in the data analysis, will be simpler. This will be further discussed in section 4.1. The new design opens for a better geometrical acceptance of events, since each individual crystal is bigger and covers a larger solid angle. An event where the proton deposits its energy in more than one crystal has previously been discarded. Possibly, these events can now be analyzed. But that requires that the energy calibration is valid for the entire energy range from 0 to 175 MeV. Until now, the calibration has been based on the assumption of a linear relationship between pulse height and deposited energy. This assumption is valid for a short energy interval only. If we want to use the full energy range, this assumption must be more carefully investigated.

3.2.3 Detector design

The same material as in the old ones, Na-doped CsI, was chosen for the new detectors. CsI(Na) is a scintillating material with a rather good energy resolution, and properties similar to materials such as NaI(Tl), but it is less hygroscopic. It has a relatively slow decay time, which is acceptable in this case. More importantly, the emission maximum of CsI(Na) peaks at 420 nm, and is well suited for PM-tube readout [20]. The size of the individual CsI crystals is restricted by two limiting factors. First, it needs to be at least 8 cm deep to stop 175 MeV protons in the detector material. Second, bigger crystals are more expensive to make. The most economical alternative was to choose a standard size offered by the manufacturer: 9 cm deep, 8 cm wide and 22 cm high. The new SCANDAL is equipped with 16 CsI scintillating detectors, eight on each arm, together covering a solid angle of approximately 0.4 sr. This is slightly smaller than in the old setup, but the angular overlap between the two arms can be decreased to maintain the total angular range covered by them.

The CsI crystals are fitted with one PM-tube each, collecting the light via a 5 mm thick silica light guide, see figure 4. The light guide is attached to the crystal with optical glue. The crystals are wrapped in white Teflon tape, about 500 µm thick, to improve the reflectivity of the walls. But because of the hygroscopic properties of Na-doped CsI, they are also wrapped in 15 µm thick aluminum foil to keep any humidity out.

The CsI detectors are placed alongside each other on an aluminum beam inside the housing, with the PM-tubes pointing up. They are held in place by two carefully fitted aluminum beams, which also serve as a connection point for grounding of the PM-tubes. The back of the housing is an aluminum sheet with feed-throughs for the high
voltage and the signal cables. The detectors themselves are not completely light tight, why the housing must be carefully sealed with black electrical tape. The front of the house is a similar aluminum sheet, but with a window the same size as the eight CsI crystals on each arm. This window is covered with a thin black plastic sheet, originally meant for storing of light sensitive photographic film.

Figure 4: The dimensions of the CsI detectors. The left figure shows an individual CsI crystal with a PM-tube. The diameter of the PM-tubes is 2 mm wider than the width of the crystal, and they are therefore glued on to the crystals slightly off center as seen to the right. The right figure, a view from above, shows how the crystals are fitted together in the setup by alternating the direction of the offset of the PM-tube.

3.2.4 Other changes

The frame and the housing of the CsI detectors were changed in order to get closer to the neutron beam. The amount of material in the beam must be minimized, to avoid a background of particles scattered elsewhere than in the target material. Therefore some of the frame material has been removed to create a free passage for the beam, see figure 5. The drift chambers remain in their original position, while the plastic scintillators have been shifted to the right on both arms.

When the iron wall, mentioned in section 3.1, was installed in the experimental hall at TSL in 2008, SCANDAL was forced 87 cm downstream. The pivot point of SCANDAL is now at 727 cm from the Li-target.

A 2 cm thick converter scintillator was chosen for the experiments at 175 MeV. A thick converter is made possible by the fact that the energy loss per unit path length in the material will be lower at higher energies. This is very welcome since the (n, p) cross section on H is roughly 30 % lower at 175 MeV than at 96 MeV [21], where previous measurements were done. A thick converter is needed to maintain a decent count rate in the experiment.
Figure 5: The differences between the old and the new SCANDAL. The left panel shows how the smallest measuring angle was limited by an iron beam in the old SCANDAL. In the new SCANDAL, seen in the right panel, the CsI housing has been extended to create a passage for the neutron beam. In the new SCANDAL, the CsI crystals are bigger, but fewer. The shape of the crystals, and how they fit together, is indicated in the bottom right corners of each panel.

3.3 Measurements

3.3.1 Calibration

The (n, p) reaction on H is used for energy calibration of the setup. For this purpose SCANDAL is run in proton mode. Pure H targets are very impractical. Instead hydrogen rich plastic is used, which provides a cheap and compact solution, even though a more advanced analysis has to be applied to the data. The multi-target box, described in section 3.2.1, is filled with five thin plastic targets of thicknesses 1 mm, 1 mm, 0.95 mm, 0.95 mm and 0.95 mm respectively, and two thin carbon targets of a thickness of 1 mm each. The design of the multi-target box makes it possible to identify in which plane the (n, p) reaction took place. After normalization with regards to the carbon content in the plastic, the carbon spectra can be subtracted from the plastic spectra, leaving a pure hydrogen spectrum. Since each plane can be analyzed individually, the geometry is very well defined and the calibration energy can be calculated to a high precision.

Using a series of thin targets, rather than one thick target, improves the energy resolution without loss of statistics, and the beam time can be kept short. A total of 6 hours of beam time was spent on calibration. Four CsI detectors are calibrated at a time, by placing them at the most forward angles possible, where the full energy peaks are most clearly visible.
3.3.2 The Fe and Bi targets

The choice of target nuclei was based on the needs for nuclear data in both applications and in the development of theoretical nuclear reaction models. Natural Fe was chosen because it is a very common construction material in almost all nuclear technology applications. $^{56}$Fe is the most tightly bound nuclei and therefore also theoretically interesting. The fact that natural iron is almost mono-isotopic in $^{56}$Fe gives a pure target. $^{209}$Bi on the other hand was chosen because it is of highest interest for future bismuth/lead cooled reactor concepts. Luckily it is also mono-isotopic by nature and quite easy to handle as a target material. It is not as poisonous as lead, which otherwise would have been the obvious choice as target nuclei because of its doubly magic nuclei, $^{208}$Pb. But because $^{209}$Bi is very close to $^{208}$Pb in mass number, it is still of great relevance to the development of theoretical models for nuclear reactions.

The targets used for cross section measurements at 175 MeV have to be rather large, because the cross sections at these energies are quite small. The Fe target is a solid cylinder with a diameter of 11.6 cm and a height of 16.0 cm, giving a total mass of 12.15 kg. The dimensions of the Bi target are not as well defined, because Bi has the peculiar property of expanding as it cools off in the casting process. But the target is approximately a 13 cm high solid cylinder with a diameter of 11 cm and its mass is 11.80 kg.

Each target has a cylindrical plastic foot to stand on at the SCANDAL table. Its thickness is designed to put the target at the right height in the beam, and its diameter is the same as the target, to make sure that we can put the target back at the exact same position when changing between the different targets during the experimental run. The target foot is not in the beam, and should not cause a scattering background.

3.3.3 Cross section measurements

The actual neutron elastic scattering cross section measurements are done in neutron mode. The multi-target box is left empty in the same position as in the calibration runs. This way it serves to reject charged particles in the neutron beam, in the off-line analysis. To reduce the background consisting of particles scattered in the Medley setup, an iron wall is built on each side of the neutron beam between the multi-target box and the scattering target. The target is placed at the pivot point of SCANDAL, see figure 3.

The beam time for the experiment in January 2009 was spent alternating between the two targets and background measurements. A total of 36 hours were spent on Fe, 53 hours on Bi and 24 hours on background.

The right and left arms were placed in such a way that they covered $8^\circ$ - $42^\circ$ and $33^\circ$ - $67^\circ$ respectively in the lab system. Towards the end of the run, when we had enough statistics in the forward angles, the right arm was also placed at $33^\circ$ - $67^\circ$ to get more statistics at larger angles.

The collimator setup used for these measurements was optimized for Medley, rather than for SCANDAL. A collimator with a defining diameter of 2 cm gave a beam diameter of 8.2 cm at the scattering target. The thickest possible Li target, 23.5 mm, was used to get a high neutron flux.

3.3.4 Data acquisition

The signals from the SCANDAL detectors are sent to the counting room at TSL, where they are handled using standard CAMAC and VME electronics. An exception is the drift chambers and the multi-target signals, which are read out via CAMAC in the experimental hall. A schematic diagram of the data handling can be seen in figure 6. The data is recorded on an event-by-event basis using SVEDAQ, a data acquisition system employed at TSL, and is written to disc.
The signals from the plastic scintillators are split into a timing and an energy branch. Signals in the timing branch from the veto and trigger scintillators are used to define an event and create a gate for read-out of the system, the master signal. A logic OR between the two PM-tubes on a plastic scintillator is used to define a hit in the respective detector. A logic AND between the two trigger scintillators, vetoed by the veto scintillator, is used to define an event in the left arm or the right arm of SCANDAL. These signals are fed to a pattern unit to register in which arm the event took place. A logic OR between the right and left arm signals defines the master signal. The time signals are fed through a CFD and the time is registered by a TDC. The pulse height of the energy signals are registered by a charge sensing ADC (QDC).

The CsI signals are amplified by pre-amplifiers in the experimental hall, and then sent to a spectroscopy amplifier in the counting room, and registered by a peak sensing ADC.

In addition, the radiofrequency (RF) of the cyclotron is used as a time reference for time-of-flight measurements of the neutrons in the beam. This signal is recorded by a TDC, which is started by the master signal and stopped by the RF signal. Furthermore, the complementary of the RF signal is used as a veto on the master signal. This means that if there is no RF, no master signal will be created.

A computer busy signal is also used as a veto on the master signal. The computer busy signal helps monitor the dead time of the system. By counting the number of pulses from a 100 Hz clock, both with and without the computer busy veto, the dead time can be determined.

The same data acquisition system as before the changes of SCANDAL is used for the new SCANDAL. Some of the CsI signal input channels on the ADC are therefore left empty. Because the pattern unit is set up in such a way that the system only reads out either the left or the right arm, it is important to use the correct input channels. In the experiment described here, channel 0-7 on the ADC were used for the left arm, and channel 16-23 were used for the right arm. In the on-line and off-line sorting of the data, the CsI detectors on the left arm show up as CsI number 1-8, and the detectors on the right arm show up as CsI number 17-24. The intermediate spectra are empty.

Next page: Figure 6: The electronics used for data acquisition. The signals are sent from the experimental hall to the counting room via coaxial cables.
4. Analysis

4.1 Energy calibration

The software ROOT [22] is used for the analysis of the SCANDAL data. The raw data is sorted and written to ROOT files by the C++ code TScandal. This code has been developed and used by many generations of PhD-students. It will not be described in detail here. After sorting, the first step in the analysis is to calibrate the CsI detectors.

The energy calibration of the new CsI detectors is done by identifying the channel numbers for two known features in the pulse height spectra of protons in the calibration runs: the pedestal channel due to events detected in other CsI crystals, corresponding to zero energy, and the full energy peak from $^1H (n, p)$ scattering. A linear relationship between pulse height and deposited energy is assumed. This assumption is valid for a short energy interval only, but it is good enough for the purposes of this analysis. Figure 7 shows how a Gaussian was fitted to the peak, using predefined tools in ROOT. The center channel of the Gaussian is taken to be the center channel of the peak. The zero-energy channel was found as shown in the figure. A calibrated spectrum can be seen in the top panel of figure 8.

The energy in the full energy peak is calculated for each CsI. It depends on the angle at which the proton was scattered. Here, the angle is defined by the center of the CsI crystal. By kinematics, protons scattered at larger angles lose more of their energy in the scattering event. The protons’ energy loss in the detector materials before it reaches the CsI is also calculated, taking into account that the path length within the materials varies with the angle.

![Figure 7: Energy calibration of the CsI detectors. The pedestal channel, corresponding to zero energy depositions, is easily identified. The center of the full energy peak is found by fitting a Gaussian to the peak.](image-url)

The advantage of the multi-target box is that the scattering plane for each event can be identified. Calibrating by looking at one single CH-target means a good resolution, but also an accurately calculated peak energy. In the present data however, the statistics in the full energy peak was too low to look at a single plane, see figure 8.
calibration was therefore done on all targets at once, which implies a broader peak and a larger uncertainty in the calculated peak energy. The pulse height for a certain energy varied with hit position in the CsI crystals in the old SCANDAL setup, because of the irregular shape of the crystals. No such correspondence was found in the new SCANDAL. This simplifies the analysis, and no corrections need to be made.

Figure 8: Energy spectra from CsI 4 from the calibration runs. In the top panel, events scattered in all multi-target planes are shown. In the bottom panel, only events scattered in a particular multi-target plane are chosen. The full energy peak is clearly visible in the top panel, but for some CsI detectors it is barely visible when a multi-target plane is singled out.
4.2 Energy resolution

By doing particle identification on the calibration data, some of the background can be reduced. Particle identification is done by plotting the energy loss in one of the plastic scintillators against the total energy measured in the CsI, so called $\Delta E-E$ technique. Such a plot can be seen in figure 9. Protons form a distinct band, and these events can be chosen in the analysis. Occasional deuterons form a band above the protons, as suggested in the figure. The zero energy depositions in the CsI detectors have been removed by applying a cut at 20 MeV. A CsI spectrum before and after particle identification can be seen in figure 10. This maneuver was expected to improve the resolution, but does not do so in all of the CsI spectra.

The total energy resolution for each CsI detector was found by fitting Gaussians to the full energy peak and to the background close to the peak, as shown in figure 11. The full width at half maximum (FWHM) of the fitted curve defines the resolution.

Using a Gaussian to describe the background is not necessarily the correct choice. At the time of writing, finding the resolution is work in progress. In figure 11 we can see that the fitted curve extends beyond the maximum energy, which indicates that the background would be better described by some other shape. But as a first step towards finding the energy resolution, this is still a helpful tool.

![Particle identification plot](image)

**Figure 9: Particle identification.** By plotting the energy loss in one of the plastic scintillators against the full energy measured in the CsI, different particles can be identified. Protons form a distinct band and these events can be chosen in the analysis, and the rest are discarded.
Figure 10: A CsI spectrum before and after particle identification. The top panel shows an energy spectrum from CsI 4 before particle identification. In the bottom panel, after particle identification, only protons remain. Zero energy depositions have also been removed. Note that the histogram in the top panel is on a logarithmic scale, while the bottom one is linear.

Figure 11: The energy resolution of the CsI detectors is found by fitting Gaussians to the full energy peak and to the background close to the peak. The full width at half maximum of the fitted curve defines the resolution.
4.3 Simulations

The new SCANDAL setup has been simulated [23], using the software MCNPX [24]. The aim is to provide supportive calculations regarding the efficiency of the plastic scintillators, especially the converter. The geometrical acceptance of events in the new detectors is also investigated. Figure 12 shows a simulated CsI spectrum, corresponding to a calibration spectrum in SCANDAL at small angles. The two peaks, separated by about 12 MeV, are protons produced on carbon and hydrogen respectively in the simulated multi-target box. The spectrum can be compared to the top panel in figure 8, showing experimental SCANDAL data, where only the hydrogen peak resolved. The measured resolution of 5.8 MeV implies that the peaks should be resolvable. It seems that the experimental data is clouded by a background of something that we do not fully understand.

![Simulated data](image)

**Figure 12: Simulated data.** A simulation of a SCANDAL calibration run, with plastic and carbon targets in the multi-target box, shows that the hydrogen and carbon peaks are clearly separated. This spectrum can be compared to the top panel in figure 8, which shows the corresponding experimental data, but at a larger angle, hence the difference in energy.

5. Results and discussion

The energy resolution obtained so far for each CsI detector can be seen in table 1. The average resolution for the new detectors is 5.8 MeV, including contributions from the neutron beam and plastic scintillators etc. From the estimation in section 3.2.1, the resolution was expected to be between 5.3 and 6.4 MeV. For two of the detectors, CsI 19 and 24, the resolution could not be determined. More work can, and will, be done to find a better fit to the background in the CsI spectra than the Gaussian seen in figure 11. The size of the angular bins used in the analysis also affects the energy resolution. This leads us to believe that the resolution can be improved still, and get closer to the lower estimate.

As noted in sections 4.2 and 4.3, there seems to be a very strong background in the data, which is not fully understood at this stage. A reason to suspect that the background situation has changed at TSL is that data from a SCANDAL experiment, carried out with the old SCANDAL but after the changes at TSL, was left unanalyzed. The
The angular resolution in the new SCANDAL is 2.3° for measurements at 175 MeV and the neutron detection efficiency is $3.6 \cdot 10^{-4}$, not taking data acquisition dead time and reaction losses in the target into account.

![Table 1](image)

Table 1: **Total energy resolution in the CsI detectors.** The calibration data is used to find the energy resolution. On average it is 5.8 MeV, except for CsI 19 and 24, where no full energy peak could be identified. $E_p$ is the energy at the full energy peak.

6. Conclusions and outlook

The conclusion that we can draw so far is that the new CsI scintillators and PM-tubes have been successfully installed on the new SCANDAL setup. The energy resolution is as expected. We have shown that it is on average 5.8 MeV, with variations, for the new detectors. This should be compared to the ground state separation in the interesting nuclei, which is typically a few MeV. However, the collected data seems to be composed of partially unpredicted elements. Before an analysis of the data can be done, this needs to be understood. This work has already started. The code used for sorting of the data is old, and needs to be adjusted not only to the new SCANDAL setup, but also to the new environment at TSL. The criteria for acceptable events must probably be revised in order to reduce the amount of background events in the analysis.

A third data set from the new SCANDAL on silicon, not described in this thesis, exists. This data was recorded in June 2009, and will probably be of similar quality as the iron and bismuth data. SCANDAL has also been used in an attempt to measure the proton contamination in ANITA, the white neutron beam at TSL. This data is under analysis at the moment.

It would be a shame if the new CsI detectors did not come to any further use in the future. SCANDAL does however suffer from old age. The drift chambers are in a poor condition and we had to run part of the experiment without a large central area in one of the drift chambers. This caused a great loss in statistics for the arm in question. The multi-target box also shows signs of exhaustion.
7. Summary in Swedish - Sammanfattning på svenska


Kärndata vid höga energier är också viktigt för utveckling av framtida reaktorkoncept, t.ex. acceleratordrivna system (ADS). Men utöver dessa tillämpningar finns också ett behov av kärndata för att utveckla de teoretiska modellerna för kärnreaktioner. Dessa modeller används flitigt vid beräkningar och simuleringar inom många områden. I databiblioteken är det i dag ont om neutrandata i energiintervallet 20-200 MeV.


De nya CsI-kristallerna är 9 cm djupa, 8 cm breda och 22 cm höga. Varje SCANDAL-arm är utrustad med åtta kristaller och tillhörande PM-rör. Tillsammans täcker de omkring 0,4 sr.

Detaljer hos SCANDAL-armarnas konstruktion har också förändrats för att kunna utföra mätningar vid mindre vinklar än vad som tidigare var möjligt. Det är viktigt att det är så lite material som möjligt i strålen för att undvika en bakgrund av spridda partiklar.

I januari och februari 2009 utfördes tvärsnittsmätningar på Fe och Bi med nya SCANDAL. Dessa data är ännu ej färdiganalyserade. En första analys av tillhörande kalibreringsdata visar att energiupplösningen är i genomsnitt 5,8 MeV för CsI-detektorer. Men analysen visar också att experimentet lider av en större bakgrund än förväntat. Analysmetoderna måste därför förfinas. Förbättrade analysmetoder kan förhoppningsvis städa upp i spektra betydligt. Den ökade bakgrunden tros bero på förändringar som nyligen har gjorts på TSL.

Nya SCANDAL har också använts för ytterligare en mätning på Si, och ett försök har gjorts att använda SCANDAL till att mäta protoninnehållet i ANITA, den vita neutron strålen på TSL. Data från dessa mätningar har ännu ej analyserats.

De slutsatser vi kan dra så här långt är att upgraderingen av SCANDAL har varit framgångsrik. CsI-kristallerna och PM-rören är installerade och fungerar. Energiupplösningen i CsI detektorerna är som förväntat. För att komma vidare med analysen av tvärsnittsdata krävs en noggrannare undersökning av vad som kan göras åt bakgrunden. Ett första steg är att förbättra de program som används för att sortera data, och anpassa dessa till den nya situationen på TSL och nya SCANDAL. Detta arbete har redan påbörjats.
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Paper 1
An upgrade of the SCANDAL facility for neutron scattering measurements at 175 MeV


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Abstract

The experimental setup SCANDAL (SCAttered Nucleon Detection AssembLy) at the The Svedberg Laboratory (TSL), previously used for measurements of the differential cross section of elastic and inelastic neutron scattering in the 50 – 130 MeV range, has recently been upgraded with new Na doped CsI scintillating detectors for measurements at 175 MeV. The performance of the new setup is described and illustrated by the early steps in the analysis of the first experimental campaign, carried out in January and February 2009.

1. Introduction

The SCANDAL setup at TSL has been used for cross section measurements of elastic and inelastic neutron scattering since 1999. Since then, the differential cross sections for a series of nuclei have been measured at the incident neutron energy 96 MeV, see [1], [2], [3], [4]. Recently the setup was upgraded with new thicker CsI scintillating detectors, and measurements have been carried out at the neutron energy 175 MeV.

Collecting nuclear data of this kind is motivated both by various applications and an improved understanding of fundamental physics. There is a shortage of neutron-induced experimental data today in the 20 - 200 MeV region. Filling this gap will help improve the theoretical models of nuclear reactions. In particular the optical model potential (OMP) [5] would benefit from elastic scattering data. The OMP is a key ingredient in nuclear reaction codes, widely used in many applications. We find three major fields of applications involving neutrons at these energies. In radiation treatment of cancer tumors, neutron therapy [6] has proven to be a good alternative in some cases where conventional radiation treatment, using photons or electrons, has failed. Neutron data is therefore needed to improve our understanding of the dose delivery to the human body.

In electronic devices, especially at high altitudes, e.g. in airplanes, cosmic-ray neutrons can induce a nuclear reaction in the silicon substrate, and thereby cause a random change of the memory content. This is obviously unwanted and the problem is referred to as single event effects [7]. Nuclear data on elastic neutron scattering is very useful in this field of research, since the elastic scattering cross section makes up the larger part of the total neutron cross section [8]. Electronics testing related to this phenomenon is routinely carried out at the neutron beam facility at TSL [9].

The third, and maybe the most obvious, field of application for this type of nuclear data is nuclear technology for energy purposes – nuclear power. Nuclear reactors of today produce radioactive waste, which is difficult to handle. Future reactor concepts, e.g. accelerator driven systems (ADS), may be a solution to this problem.

The results from previous cross section measurements of elastic neutron scattering on H, D, C, O, Fe, Y and Pb, at 96 MeV, using the experimental setup SCANDAL, show good agreement with theoretical predictions, see e.g. [1], [2]. From some of these data sets, information on inelastic scattering has also been extracted, and a publication with data for C, Fe, Y and Pb is currently in preparation [10]. The new detectors on SCANDAL are designed for measurements of elastic, and possibly inelastic, scattering at 175 MeV, which is the maximum neutron energy available at TSL [11]. This paper reports on the performance of the new CsI scintillating detectors, and other changes of the SCANDAL setup.

2. SCANDAL

2.1 Overview

A brief overview of the SCANDAL setup is given here, since it has previously been described in great detail, e.g. [12]. A schematic picture of the setup can be seen in figure 1. The scattering target is placed on a table in front of the two identical SCANDAL arms. Each arm can be swung into the desired
angle, together typically covering angles between 10° and 70° in the lab system. The arms are usually put in such a way that their angular range have a slight overlap, to get a cross check of systematical errors between the two arms. It is also desirable to put one of the arms as close to the beam as possible, to measure at small angles. This is important for normalization of the measured cross section, since elastic scattering peaks at forward angles. The data is normalized to the well known total cross section. The limiting factor of how close to the beam we can get is the housing of the detectors, since any material in the beam will cause an unwanted background of scattered particles. The SCANDAL arms are flexible enough to be turned all the way around for measurements beyond 90°.

When a neutron has been scattered in the target, it passes through the veto scintillator, which is a 2 mm thick plastic scintillator, 60 cm wide and 30 cm high. Its chemical composition is C₂H₁₁. The scintillator serves to reject charged particles produced in the target, by acting as a fast veto on the trigger signal for the data acquisition system. The second detector is the active converter, where the neutron is converted into a proton in the reaction H (n, p). It is a 20 mm thick plastic scintillator, 60 cm wide and 30 cm high, and measures the energy loss of the recoil proton in the converter material. Since the energy loss can be compensated for when using an active converter, it is possible to use a thicker converter without impairing the energy resolution.

The angle of the outgoing particle may change relative to the incoming particle in the conversion. Therefore two drift chambers [13] record the path of the outgoing proton. The proton path determines the conversion point, and the scattering angle of the original neutron can be calculated. However, conversion on carbon might also occur in the plastic of the converter scintillator. But as this reaction has a Q-value of -12.6 MeV, protons scattered on H at angles smaller than 15° can be identified on the basis of their energy. Protons scattered on H at larger angles than 15° on the other hand, will lose more than 12.6 MeV due to kinematics, and cannot be distinguished from protons produced on carbon. In the analysis, the drift chamber information can be used to discard all events with a conversion angle above 15°.

A 2 mm thick plastic scintillator, 60 cm wide and 30 cm high, is placed in front of the drift chambers, and a 2 mm thick plastic scintillator, 75 cm wide and 30 cm high, is placed behind them. Coincident signals from these two define a trigger criterion for the data acquisition. The very last detector at the back of the SCANDAL arms is an array of CsI crystals. They measure the full energy of the protons, which is necessary for distinguishing between protons originating from elastically scattered neutrons, and protons originating from inelastically scattered neutrons. The energy losses in the plastic scintillators are recorded, and the total energy can be corrected for these losses event by event. SCANDAL can be operated in both neutron mode and proton mode. If the signal from the veto scintillator is used as a veto in the data acquisition trigger, only neutrons will be recorded. If we instead require a triple coincidence between the veto, trigger one and trigger two scintillators, then only charged particles will be recorded. Protons can be distinguished from other charged particles in the off-line analysis using ΔE-E techniques, see section 5.1. Proton mode is used for energy calibration of the detectors, see section 4.2.

An optional feature of SCANDAL is the multi-target box, which sits upstream of the position of the scattering target, see figure 1. It is mainly used for calibration purposes, but can, if left empty, also be used for rejection of charged particles in the neutron beam during cross section measurements. The rejection of charged particles is then done in the off-line analysis. Seven different scattering targets can be placed in the multi-target box at the same time. The target planes are separated by multi-wire proportional counters, which means that for (n, p) reactions the scattering plane for each event can be identified. A more detailed description is given in ref. [14].

The detection efficiency of SCANDAL varies with the neutron beam energy because of varying reaction cross sections. Typically, cross sections are smaller for higher energies, which gives a lower detection efficiency. The neutron detection efficiency consists of two parts: the conversion efficiency and the proton detection efficiency. The conversion efficiency depends on the (n, p) cross section for hydrogen, the converter thickness and the accepted conversion angle. For 175 MeV neutrons, 20 mm thick converter and an accepted conversion angle of 15°, it is 6.1 - 10⁻⁴. The proton detection efficiency consists of many parts: the efficiency of the drift chamber planes, correct drift chamber wire selection in the analysis in case of double hits and the CsI response. The efficiency of the drift chamber planes is assumed to be the same at 175 MeV as at 96 MeV. It has been estimated to be 0.93 for each drift chamber plane [12]. The total contribution from the four planes is thus 0.75. The
analysis of the data will show how common double hits are, but previous experience shows that the contribution to the detection efficiency is about 0.93 from the wire selection process. The CsI full energy deposition efficiency is estimated to be 0.83 at 175 MeV. This is based on an investigation of CsI(Tl) detectors, previously carried out at the same beam line at TSL [15]. This points towards a proton detection efficiency of about 0.6 at 175 MeV. For estimation of the count rate in the experiment, the dead time of the data acquisition system and neutron reaction losses in the target have to be taken into account as well. The reaction losses in the Fe target are estimated to be about 20%.

The angular resolution achieved in SCANDAL depends on the size of the scattering target and the beam diameter. It will be worse at higher energies, because we have to use larger targets and beam size, once again because of smaller cross sections at higher energies. Using a target of about 11 cm in diameter, as in the latest measurements, and a beam diameter of 8.2 cm, the angular resolution is about 2.3° (rms).

Figure 1: A schematic figure of the SCANDAL setup. The neutron beam leaves the Medley setup, at the bottom of the picture, and passes through the multi-target box and the scattering target on the table. It continues through parts of the right SCANDAL arm, which have been designed to allow measurements at small angles close to the beam, but with as little material as possible in the beam. The scattered neutrons are detected by conversion to protons. A typical event is illustrated by a neutron and a proton path.

The old SCANDAL setup had an energy resolution of 3.7 MeV, to which the CsI detectors contributed 3.0 MeV [12]. There are four contributions to the energy resolution: the width of the full energy peak in the neutron beam, straggling in the plastic scintillators, straggling in other materials and the resolution of the CsI detectors. The first three of these contributions are 2.5 MeV, 1.9 MeV and 1.1 MeV respectively in the new SCANDAL. The estimations of the contributions from straggling in different materials are based on calculations of stopping ranges calculated using the SRIM software.
It is reasonable to expect the energy resolution in the CsI detectors to be roughly proportional to the square root of the energy. Assuming that the new CsI detectors behave in a similar way to the old ones, a resolution of 4.1 MeV can be expected for the new detectors at 175 MeV. This would mean a total resolution of 5.3 MeV for the new setup.

As a worst-case scenario, if the energy dependence of the resolution is linear, the energy resolution of the CsI detectors can be closer to 5.5 MeV. For the new setup this would result in an energy resolution of 6.4 MeV at 175 MeV. The actual measured energy resolution is discussed in section 5.3.

2.2 Upgrades of SCANDAL

2.2.1 CsI crystals and PM-tubes

The CsI crystals of the old SCANDAL setup were not deep enough to cover the top end of the energy range of the neutron beam at TSL. Protons of 175 MeV would have been able to pass through the detectors without depositing their total energy in the CsI crystal. SCANDAL has therefore been upgraded with larger, and more suitably shaped, Na-doped CsI crystals and PM-tubes.

A detector depth of about 8 cm is required to fully stop 175 MeV protons in the detector material [16]. The new SCANDAL is equipped with 16 CsI scintillating detectors, eight on each arm, with an individual surface area of 8 cm x 22 cm and a depth of 9 cm, see figure 2. Together they cover a solid angle of approximately 0.4 sr (0.2 sr for each arm). Each CsI crystal is fitted with a PM-tube, collecting the light via a 5 mm thick silica light guide. The light guide is attached to the crystal with optical glue. The crystals are wrapped in white Teflon tape, about 500 µm thick, to improve the reflectivity of the walls. But because of the hygroscopic properties of Na-doped CsI, they are also wrapped in 15 µm thick aluminum foil to keep any humidity out.

The CsI detectors are placed alongside each other on an aluminum beam inside the housing on the SCANDAL arms, with the PM-tubes pointing up. They are held in place by two carefully fitted aluminum beams, which also serve as a connection point for grounding of the PM-tubes. The back of the housing is an aluminum sheet with feed-throughs for the high voltage and the signal cables. The detectors themselves are not completely light tight, why the housing must be carefully sealed with black electrical tape. The front of the house is a similar aluminum sheet, but with a window the same size as the eight CsI crystals on each arm. This window is covered with a thin black plastic sheet, originally meant for storing of light sensitive photographic film.

Figure 2: The dimensions of the CsI detectors. The left figure shows an individual CsI crystal with a PM-tube. The diameter of the PM-tubes is 2 mm wider than the width of the crystal, and they are therefore glued on to the crystals slightly off center. The right figure, a view from above, shows how they are fitted together in the setup by alternating the direction of the offset.
2.2.2 Changes of the SCANDAL frame

The frame and the housing of the CsI detectors were also changed, in order to get closer to the neutron beam. The amount of material in the beam must be minimized, to avoid a background of particles scattered elsewhere than in the target material. Therefore some of the frame material has been redesigned to create a free passage for the beam. The differences between the old and new SCANDAL can be seen in figure 3.

Figure 3: The differences between the old and the new SCANDAL. The left panel shows how the smallest measuring angle was limited by an iron beam (highlighted in grey) in the old SCANDAL. In the new SCANDAL, seen in the right panel, the CsI housing has been extended to create a passage for the neutron beam. In the new SCANDAL, the CsI detectors are bigger, but fewer. The shape of the crystals, and how they sit together, is indicated in the bottom right corner of each panel.

2.2.3 Consequences of the upgrades

SCANDAL can now measure neutron scattering at energies up to 175 MeV. As mentioned in section 2.1, the angular resolution depends on the size of the target and the beam rather than the setup itself. But it will be worse at higher energies, because we have to use larger targets and beam size. The detection efficiency also varies with the neutron beam energy because of varying reaction cross sections. The right angles of the CsI crystal walls in the new detector design mean that any corrections, concerning hit position within the crystal, which might have to be applied in the data analysis, will be simpler. The new design also gives a better geometrical acceptance of events, since each crystal is bigger and covers a larger solid angle. Together they do however cover a smaller solid angle than the old ones, because they are fewer. But the angular overlap between the two arms can be decreased to maintain the total angular range covered by them.

The smallest scattering angles are of greatest importance for normalization of neutron data. The elastic neutron scattering falls off quickly between 0˚ and 10˚, meaning that even the tiniest improvement of how close to 0˚ we can measure will be important. The combined effect of measurements at smaller angles and the larger CsI detectors, allowing a better geometrical acceptance, will lead to a smaller uncertainty in the normalization.

A 2 cm thick converter scintillator was chosen for the experiments at 175 MeV. A thick converter is made possible by the fact that the energy loss per unit path length in the material will be lower at higher energies. This is very welcome since the \((n, p)\) cross section on H is roughly 30 % lower at 175 MeV than at 96 MeV [17], where previous measurements were done. A thick converter is needed to maintain a decent count rate in the experiment.
3. The TSL neutron beam facility

3.1 Overview

The neutron beam facility at TSL can be seen in figure 4. It is described in detail in ref. [11]. Protons from the cyclotron hit a lithium target and produce a quasi mono-energetic neutron beam. The reaction employed is $^7\text{Li}(p,n)^7\text{Be}$. A Li target thickness of 23.5 mm is used for SCANDAL experiments, but thinner ones are available, down to 2 mm. TSL can deliver a neutron beam in the energy range 1 - 175 MeV. After the lithium target, the protons in the beam are deflected by a magnet into a well shielded proton beam dump 10 meters away. The neutron beam continues through a 2 m long set of iron collimators into the experimental hall, which is on the other side of an iron wall. SCANDAL experiments are often run in parallel with the experimental setup Medley [18] that measures light ion production. In these cases, Medley is positioned upstream of SCANDAL. The Medley vacuum is terminated by a 0.1 mm thin stainless steel window, and the targets used are typical less than 0.5 mm thick.

The pivot point of SCANDAL is 727 cm downstream from the lithium target. About 9 meters further down the line is the neutron beam dump. For monitoring of the neutron flux there is a thin film breakdown counter [19] and an ionization chamber monitor in the neutron beam and a Faraday cup at the proton beam dump.

The energy spectrum for the quasi mono-energetic neutron beam has a full energy peak, containing about 40 % of the neutrons, and a low energy tail [11]. In the data analysis, the low energy neutrons can be suppressed using time-of-flight techniques, where the radio frequency from the cyclotron serves as a time reference.

The user at TSL can choose between different collimator sets. There are a number of collimator openings available in the 2 – 30 cm range. For SCANDAL and Medley runs, conical collimators, following a cylindrical part with a defining diameter of 2 cm, are usually used, which gives a beam diameter of 8.2 cm at the SCANDAL target.

3.2 Recent changes at TSL

A new neutron beam facility was built at TSL in 2004, with emphasis on high neutron beam intensity [11]. For this purpose the distance between the Li target and the experimental area was shortened. The neutron flux was thereby increased by about an order of magnitude. The experimental area now extends from 3 to 15 m downstream from the Li target.
Since 2008, an iron wall can be erected between the lithium target and the user area for additional shielding. It can be seen in figure 4. When the iron wall was installed in the experimental hall, SCANDAL was forced 87 cm downstream to its present position 727 cm from the Li target.

4. Experimental procedure

4.1 Data acquisition

The signals from the SCANDAL detectors are sent to the counting room at TSL, where they are handled using standard CAMAC and VME electronics. For a full description of the data acquisition system, see ref. [4]. The data is recorded on an event-by-event basis using SVEDAQ, a data acquisition system employed at TSL, and is written to disc. The same data acquisition system as before the changes of SCANDAL is used for the new SCANDAL. Some of the CsI signal input channels are therefore left empty, since the detectors have decreased in number.

4.2 Calibration and energy resolution measurements

The first experiment with the new SCANDAL was carried out during three weeks in January and February in 2009. During the first days of the campaign a few runs in proton mode were devoted to calibration. The (n, p) reaction on H is used for calibration of the setup, but pure H targets are very impractical. Instead hydrogen rich plastic is used. The multi-target box is filled with five thin plastic targets of thicknesses 1 mm, 1 mm, 0.95 mm, 0.95 mm and 0.95 mm respectively, and two thin carbon targets of a thickness of 1 mm each. The design of the multi-target box makes it possible to identify in which plane the (n, p) reaction took place. After normalization, with regards to the carbon content in the plastic, the carbon spectra can be subtracted from the plastic spectra, leaving a pure hydrogen spectrum. Since each plane can be analyzed individually, the geometry is very well defined and the calibration energy can be calculated to a high precision. Using a series of thin targets, rather than one thick target, improves the energy resolution without loss of statistics, and the beam time can be kept short. A total of 6 hours of beam time was spent on calibration. Four CsI detectors were calibrated at a time, by placing them at the most forward angles possible, where the full energy peaks are most clearly visible.

4.3 Experimental program

The idea of SCANDAL is to measure cross sections on a series of relevant nuclei. The obvious nuclei to study, for theoretical reasons, are the magical or semi-magical nuclei, $^{12}$C, $^{16}$O, $^{40}$Ca, $^{90}$Zr and $^{208}$Pb. Other elements common in various applications, such as Fe, U and Si are also interesting. Already, three data sets have been recorded, but not yet analyzed. For the first experimental run, iron and bismuth were chosen as target nuclei. The beam time, in total 120 hours of data collection, was shared between the two targets and background measurements. Natural Fe was chosen because it is a very common construction material in almost all nuclear technology applications. $^{56}$Fe is also the most tightly bound nuclei and therefore theoretically interesting. Natural iron is almost mono-isotopic, which gives pure targets. Because $^{205}$Bi is very close to $^{208}$Pb in mass number, it is of great relevance to the development of theoretical models for nuclear reactions. Luckily it is also mono-isotopic by nature and quite easy to handle as a target material. But $^{209}$Bi was also chosen because it is of highest interest for future bismuth/lead cooled reactor concepts. For the second experimental run, carried out in June in 2009, the scattering cross section for silicon was measured. Data on Si is important for the understanding of radiation damage to electronic devices. Together with Fe and Bi, it also contributes to cover a wide range of mass numbers. Just like iron, silicon is close to mono-isotopic in nature. SCANDAL is a versatile instrument, since it can be run in both proton mode and neutron mode. An attempt has been made to measure the proton content in ANITA [20], the white neutron beam at TSL, by putting one of the SCANDAL arms in the beam. The results from this test will be reported later.
5. Analysis and results

5.1 Data reduction

The CsI detectors record the energy of the incoming protons. In the spectrum from the calibration run we expect to see a full energy peak of recoil protons from hydrogen in the plastic targets in the multi-target box. We also expect to see a peak of protons created on carbon, in both the carbon targets and the plastic targets, separated from the H-peak by 12.6 MeV. At lower energies we expect a continuum of protons and other charged particles from reactions on carbon. A raw CsI energy spectrum can be seen in figure 5. The hydrogen peak is visible, but the carbon peak is not. The pedestal at zero energy consists of events detected in other CsI detectors.

The SCANDAL data is analyzed using the ROOT software from CERN laboratories [21]. A major part of the background events can be removed from the spectra by particle identification. When plotting the energy loss in one of the plastic scintillators against the energy measured in the CsI for each event, the protons form a band in the plot, as seen in figure 6. These events can be chosen for analysis. Occasional deuterons form a band above the protons, as suggested in the figure. The zero energy depositions in the CsI detectors have been removed by applying a cut at 20 MeV. What remains in the CsI spectra after particle identification can be seen in figure 7.

![Energy Spectrum](image)

Figure 5: CsI energy spectrum from the calibration run. This spectrum shows the energy deposited in CsI 4, at about 30° in the lab system, during a calibration run where SCANDAL is run in proton mode and there are both plastic and carbon targets in the multi-target box. The full energy peak, consisting of protons from hydrogen in the plastic targets, can be identified. But the expected carbon peak is not visible. The pedestal at zero energy is due to events detected in other CsI detectors. This figure can be compared to figure 10, which is a simulation of the same setup, but at a smaller scattering angle, hence the higher energy in the H-peak.
Particle identification.

By plotting the energy loss in one of the plastic scintillators against the full energy measured in the CsI, different particles can be identified. Protons form a distinct band and these events can be chosen in the analysis, and the rest are discarded.

Figure 6: Particle identification. By plotting the energy loss in one of the plastic scintillators against the full energy measured in the CsI, different particles can be identified. Protons form a distinct band and these events can be chosen in the analysis, and the rest are discarded.

A CsI spectrum after particle identification. This figure shows an energy spectrum from CsI 4 after particle identification. Zero energy depositions have also been removed.

5.2 Calibration

The energy calibration of the new CsI detectors is done by identifying the channel numbers for two known features in the pulse height spectra of protons in the calibration runs: the pedestal channel due to events detected in other CsI crystals, corresponding to zero energy, and the full energy peak from (n, p) scattering. A linear relationship between pulse height and deposited energy is assumed. This assumption is valid for a short energy interval only, but it is good enough for the purposes of this analysis. The pedestal channel is easily found by looking at the raw spectra. Fitting a Gaussian to the full energy peak identifies the center channel number. An example of this is shown in figure 8. The energy for this channel number is obtained by calculating the energy of the scattered proton at this particular angle, and the loss of energy between the scattering target and the CsI, taking into account that the path length within the materials varies with the angle. A calibrated spectrum is shown in figure 5.

The pulse height for a certain energy varied with hit position in the CsI crystals in the old SCANDAL
setup, because of the irregular shape of the crystals. No such correspondence was found in the new SCANDAL. This simplifies the analysis, and no corrections need to be made.

Figure 8: Energy calibration of the CsI detectors. The pedestal channel, corresponding to zero energy depositions, is easily identified as shown in the figure. The center of the full energy peak is found by fitting a Gaussian to the peak. The calibrated spectrum is shown in figure 5.

5.3 Energy resolution

When the calibration of the CsI detectors is done, their energy resolution of the setup can be determined. The energy resolution of the CsI detectors was found by fitting Gaussians to the full energy peak and to the background close to the peak, as shown in figure 9, using predefined tools in ROOT. An example is shown in figure 9. The full width at half maximum (FWHM) of the fitted Gaussian defines the resolution. The resolution was found to be on average 5.8 MeV, ranging from 4 to 8 MeV in the different CsI detectors.

Figure 9: The energy resolution of the CsI detectors is found by fitting a Gaussian to the full energy peak. The full width at half maximum of the fitted curve defines the resolution.

Using a Gaussian to describe the background is not necessarily the correct choice. At the time of writing, finding the resolution is work in progress. In figure 9 we can see that the fitted curve extends beyond the maximum energy, which indicates that the background would be better described by
some other shape. For the purpose of finding an upper limit of the energy resolution, this is still a helpful tool.
Performing the same procedure on the data before and after particle identification showed that no improvement of the resolution was to be found this way. Nor does the resolution improve from other cuts that can be applied, because of the great loss of statistics that they cause.

5.4 Simulations

The new SCANDAL setup has been simulated [22], using the software MCNPX [23]. The aim is to provide supportive calculations regarding the efficiency of the plastic scintillators, especially the converter. The geometrical acceptance of events in the new detectors is also investigated. Figure 10 shows a simulated CsI spectrum, corresponding to a calibration spectrum in SCANDAL at small angles. The two peaks, separated by about 12 MeV, are protons produced on carbon and hydrogen respectively in the simulated multi-target box. It can be compared to figure 5, showing experimental SCANDAL data, where only the hydrogen peak resolved. The measured resolution of 5.8 MeV implies that the peaks should be resolvable at small angles. It seems that the experimental data is clouded by a background of something that we do not fully understand.

![Simulated data](image)

**Figure 10:** Simulated data. A simulation of a SCANDAL calibration run, with plastic and carbon targets in the multi-target box, shows that the hydrogen and carbon peaks are clearly separated. This spectrum can be compared to figure 5, which shows the corresponding experimental data, but at a larger angle, hence the difference in energy.

6. Conclusions and outlook

The conclusion that we can draw so far is that the new CsI scintillators and PM-tubes have been successfully installed on the SCANDAL setup. The analysis of the acquired data shows that particle identification and calibration can be done successfully with the new setup, as shown in the previous sections. The energy resolution is on average at least 5.8 MeV for the new detectors.

It seems that a major part of the recorded data consists of a background that we do not fully understand. Possibly this contribution can be reduced by optimizing the off-line sorting routines and adjust them to the new situation with higher energy neutrons and different detectors. This work has already started.
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