5. First feasibility experiment for EXL

It is a well-known fact that the study of light-ion induced direct reactions, like elastic and inelastic scattering, transfer, and charge-exchange reactions, provides important information on the structure of nuclei. Hence, elastic and inelastic scattering experiments with light projectiles like proton have been routinely performed in the past [52]. Before having the radioactive ion beams (RIB) available, such studies were limited to the use of stable or long-lived nuclei as targets in normal kinematics experiments. But with the advent of RIB facilities there is a possibility to extend the nuclear structure investigations to exotic nuclei as well. In this way, virtually the whole chart of the nuclei opens up for research so that theoretical models can be tested and verified all the way up to the limits of nuclear existence: the proton and neutron drip lines [53] (see also Fig. 1.1). In particular, using stored radioactive beams and exploiting reactions in inverse kinematics inside a storage ring using thin internal targets enables, comparing to investigations with external targets, high resolution measurements down to very low momentum transfers. This technique allows, in many cases, to deduce essential nuclear structure information. It also provides a gain in luminosity from accumulation and recirculation of the radioactive beams [54]. The high luminosities provided in these kinds of ring experiments compensate for the very thin targets which permit the low-energy scattered target-like recoil ions to make it through the target-beam interaction region and to enter the detectors installed around the target without major distortion of energy and angular resolution. The possibility of studying these low-energy recoil particles is especially important when getting away from the region of stable nuclei, since it will allow us to study the periphery of exotic nuclei. For example, one of the most outstanding discoveries was the finding that the nuclear matter may appear under certain conditions with a qualitatively new type of nuclear structure, so-called “halo” structure [36, 37]. It magnifies, among other nuclear structure aspects, the importance of studying such systems in the limits of very low momentum transfers. In particular, \((p,p)\) scattering at low \(q\) has turned out to be an excellent tool for the investigation of halo structures [12, 55]. Other aspects like the in-medium interactions in proton-neutron asymmetric nuclear matter, giant resonances with strength distributions totally different from those known in stable nuclei, the shell structure in nuclei of extreme proton-to-neutron asymmetry leading to disappearance of the known magic numbers and, in turn, to the appearance of new shell gaps could also be studied well in the low momentum transfer region. These were all the motivations to start with the design of a new detection system in the framework of the upcoming FAIR facility. In order to perform a feasibility study for the EXL setup [10] at the NESR storage
In this chapter the experimental setup and data for EXL, the recoil Si-detector was mounted close to the target position. The positions of systems and the background conditions in a realistic storage ring scenario (results in December 2005 at GSI Darmstadt, Germany). In this feasibility test, we used the ESR storage ring, a test experiment was set up at the existing storage ring ESR (see Fig. 5.1) in December 2005 at GSI Darmstadt, Germany. In this feasibility test, we used the ESR storage ring to study the reactions resulting from the interaction of a stable $^{136}$Xe beam with an internal hydrogen target.

The test experiment was intended to investigate the performance of the detector systems and the background conditions in a realistic storage ring scenario (results partly published in [11] and [56]). In this chapter the experimental setup and data
For the feasibility experiment, detector elements representing all the major detector systems of the future EXL setup, along with an internal hydrogen gas-jet target were installed at the ESR (Fig. 5.2). Most of the various detector elements in this experiment covered only a small fraction of the total available phase space. A \(^{136}\text{Xe}\) beam with an energy of 350 MeV/nucleon was injected into the ESR from the heavy-ion synchrotron SIS, periodically exposed to electron cooling and moderately bunched.

**Figure 5.2:** Experimental setup for the EXL test experiment performed at the storage ring ESR at GSI. For details see the text.
Chapter 5: First feasibility experiment for EXL

by an RF cavity. We had two bunches of totally 100 ns length; the circumference of the ESR storage ring was about 108 m (≈ 500 ns for this energy). The beam storage lifetime was found to be about 30 min; on average more than $10^9$ ions were circulating with a revolution frequency of $2 \times 10^6$/s, scattering off the internal hydrogen gas-jet target (with a thickness of $\approx 10^{12}$ atoms/cm$^2$) which was installed inside the vacuum chamber (for an introduction to the ESR internal target, see appendix B).

The detector setup for fast ejectiles consisted of two arrays with a total of 15 organic scintillators, each coupled with an iron converter, for detection of fast neutrons and light charged particles which are produced and can be detected mostly at forward angles due to their relativistic velocities. The two scintillator arrays were installed at about 230 cm and 400 cm downstream from the target (Figs. 5.2 and 5.3). Every scintillator and iron element had a rectangular cuboid shape with the dimensions of $10 \times 50 \times 4$ cm$^3$ and $10 \times 50 \times 5$ cm$^3$, respectively. Each iron-scintillator couple was mounted in such a way that we had 4 cm of scintillator material in the beam direction preceded by 5 cm iron. In total we had eight iron-scintillator couples put together in a square-like frame making the first array and seven put together as a wall making the second array.

For detection, identification, and fast timing of the beam-like reaction products we had a position sensitive silicon p-i-n diode (of 300 µm thickness and $45 \times 45$ mm$^2$ surface area) followed by a 1 mm thick scintillation detector. They were installed further downstream the target after the first dipole magnet in a movable vacuum pocket driven in and out of the beam tube. Furthermore, a multi-wire proportional chamber (MWPC) for detection of the product of atomic charge-exchange reactions and a photomultiplier (PM) for additional luminosity measurements were

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.3.png}
\caption{Top view of the organic scintillators used for detection of fast ejectiles. The angular ranges that are shown here represent the range of the scattering angle $\theta$ that covers the whole of the two detector layers labeled as “1$^{st}$ layer” and “2$^{nd}$ layer”. Note that the iron converters in front of the scintillator bars are not shown here.}
\end{figure}
5.1. Experimental setup

mounted outside the UHV (Ultra High Vacuum) reaction chamber. A UHV compatible single-sided Si-strip detector (Fig. 5.4) of 1 mm thickness and $40 \times 40$ mm$^2$ area (total of 40 strips) for detection of the target-like reaction products was the only detector element mounted inside the UHV of the vacuum chamber. The detector

![Figure 5.4: Photograph of the UHV compatible Si-strip detector used in the EXL test experiment, together with the mounting flange and the wiring.](image)

was designed [57] on the basis of a special vacuum compatible ceramic support and connected to the preamplifiers located outside of the reaction chamber via homemade copper wires with glass pearls acting as isolation. The Si-strip detector was read out in five groups of silicon strips, each of which with eight strips, and was used to detect the recoil protons. Energy deposition and position of the particles were reconstructed using a charge-division method (Fig. 5.5). The detector was first tested with an $^{241}$Am $\alpha$-source and an energy resolution of 27 keV at 5.6 MeV (0.5%) was obtained (Fig. 5.6). It also showed a very good position resolution in terms of having well separated peaks (Fig. 5.7). The UHV conditions in the storage ring and the necessary baking of anything placed in it require that they are resistant to high temperatures. The Si-strip detector was tested and it was shown that it can withstand temperatures of up to 200$^\circ$ Celsius [58].

Geometrically, the silicon detector edges were placed at angles of about 89.5$^\circ$ and 73.4$^\circ$ with respect to the beam direction ($z$-axis) in such a way that the normal vector to the detector surface, passing through the mid-point of the detector, points straight to the center of the interaction point inside the target chamber (Fig. 5.8). The distance of the mid-point of the detector square surface to the target point was about 14.3 cm. To protect the detector from the UV light coming from beam-target interactions, a thin nickel foil of 1 $\mu$m thickness was mounted in front of it.
**Figure 5.5:** Charge-division readout for the Si-strip detector. The sum of signal 1 and signal 2 gives the energy deposited in the detector, and their ratio gives information about the coordinate of the particle [11].

**Figure 5.6:** Energy spectrum of individual strips of the Si-strip detector, tested with an $^{241}$Am $\alpha$-source. The fit is a Gaussian with $mean = 5637.11 \pm 0.02$ keV and FWHM = $27.33 \pm 0.02$ keV [11].
5.2. Luminosity monitors

During the test experiment the beam was moved horizontally along the $x$-axis (perpendicular to the beam axis and the direction of the gas-jet injection) over the target.
in order to measure the extension of the interaction profile by different relative luminosity monitors. Three detector elements were used to measure the relative luminosity: a MWPC that was used to detect the \((\text{Xe}^{54+} \rightarrow \text{Xe}^{53+})\) beam ions deflected out of the central orbit of the ring after atomic charge exchange, a photomultiplier installed close to the target that was used to detect UV light produced from the beam-target interaction, and the silicon detector that was used to detect the recoil light particles. The interaction profiles obtained from these three detectors are in good agreement and shown in Fig. 5.9. The size of the target profile is obtained to be about 7.4 mm (FWHM) after unfolding the beam size which was estimated to be about 5 mm in diameter. The absolute luminosity was calculated measuring the beam intensity (by means of a current transformer) and the target density and reached a maximum value of \((6 \pm 2) \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}\). The target density was constantly recorded during the experiment and the beam intensity was also registered.

![Figure 5.9: The interaction profile as measured by three different detection systems [57]. Asterisks, hollow squares, and hollow circles represent data from MWPC, Photomultiplier (PM), and Si-detector, respectively. For the sake of clarity, the data points of PM and Si-detector are shifted a bit to the right and the left side of the MWPC data, respectively. The fit is made to the MWPC data. The interaction profile has a width of 8.95 ± 0.22 mm (FWHM).]
during each period of data acquisition (run) with cooled and stabilized beam. For a specific run with the duration of 18976 seconds, the registered ESR beam current was about 6.16 mA and the average target density during the run time was obtained to be about $2.29 \times 10^{12}/\text{cm}^2$ (the target density was recorded every 3 seconds). This results in an averaged luminosity of about $1.6 \times 10^{27} \text{cm}^{-2} \text{s}^{-1}$ for a fully stripped $^{136}\text{Xe}$. This is comparable to the luminosity calculated from the nominal values of the average number of ions circulating in the ring ($\approx 10^9$) and the revolution frequency of ions ($\approx 2 \text{ MHz}$).

![Deposited Energy vs Counts](image)

**Figure 5.10**: Identification of the reaction channels. The top panel shows the deposited energy (in MeV) of heavy ions in the p-i-n diode. Here, all the reaction products are registered. In the middle panel the reaction channels are differentiated through requiring a coincidence between two coupled detectors in the first series of scintillators (the two detectors labeled as “1st layer” and “2nd layer” in Fig. 5.3). The spectrum of the first panel clearly shows the dominance of singles channel, when compared to the middle panel in terms of the amount of statistics after requiring coincidence. The bottom panel shows the Geant4 simulation results for $^{135}\text{I}$ and $^{135}\text{Xe}$ ions of 350 MeV/nucleon that are detected by the p-i-n diode in the reaction channels $^{136}\text{Xe}(p, 2p)$ and $^{136}\text{Xe}(p, np)$, respectively. The left peak corresponds to I isotopes and the right one to Xe. The results of the upper two panels are calibrated to the simulation results for the Xe peak.
5.3 Detection of beam-like particles and forward ejectiles

The detection system for beam-like reaction products in the ESR test experiment consisted of a silicon p-i-n diode detector with a thickness of 300 µm and an area of $45 \times 45$ mm$^2$ followed by a thin scintillator of 1 mm thickness, which was used for triggering and fast timing of the beam-like particles. The system was installed about 21 m downstream from the target ($\approx 6$ m after the dipole magnets; see Fig. 5.2). The energy resolution of the scintillator did not allow for isotope separation; thus, the energy loss of heavy-ions was measured by the p-i-n diode. There was a possibility for the p-i-n diode to be moved in and out of the ring; during the refilling of the ESR ring and before the beam was cooled down we needed to bring out the detector in order to keep it away from any possible radiation damage caused by the direct intense beam. This feature allowed us as well to change the distance of the detector with respect to the center of the ring during the experiment (the surface of the detector was perpendicular to the beam direction). This way, one could scan for the heavy ions deflected from the beam direction, which are basically those which undergo an interaction.

Using the combination of the heavy-ion detection setup and the two series of scintillator assemblies, installed about 2.3 m and 4 m downstream of the target, one can identify different reaction channels like $(p,n)$, $(p,p\alpha n)$, and $(p,2p\alpha n)$. In such reactions there is a possibility that the light ejectiles, emitted at forward angles due to relativistic velocities, are detected by the scintillator arrays in coincidence with the beam-like particles hitting the small area p-i-n diode. The result of such a coincidence measurement is shown in Fig. 5.10 (middle panel). We also used the Geant4 package to compare data with simulations. Comparing to the results of the simulations (bottom panel), it reveals the identification of at least two reaction channels, namely $^{136}\text{Xe}(p,\alpha n)$ and $^{136}\text{Xe}(p,2p\alpha n)$. The simulations are performed for $^{135}\text{Xe}$ and $^{135}\text{I}$ of 350 MeV/nucleon.

Fig. 5.11 shows the deposited energy in the two consecutive scintillator layers of the first series of the fast ejectile scintillators (see Fig. 5.3). The results are from data analyses and simulations in Geant4 and Geant3 as well. The Geant3 results were obtained using the Virtual Monte Carlo (VMC)$^1$ package. The two simulation results of Geant3 and Geant4 are in good agreement. There is a small peak, appearing at around 20 MeV, in the simulated spectrum of the “2nd layer” which is not present in the experimental data. It is built up by those protons which are scattered at angles around 3.7° (see Fig. 5.3) and hit the “1st layer” at the upper edge while they miss the first iron layer before this scintillator layer. Thus, the small peak appears more or less at the same position as that of the peak of the “1st layer”.

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1 The Virtual Monte Carlo provides an abstract interface into the Monte Carlo transport codes: Geant3, Geant4 and Fluka. The user VMC based application, independent from the specific Monte Carlo codes, can then be run with all three simulation programs. [59]
5.3. Detection of beam-like particles and forward ejectiles

Figure 5.11: Deposited energy (in MeV) in the two consecutive layers of the first series of fast ejectile scintillators (shown in Fig. 5.3). On the left side the experimental spectra are shown. These spectra were obtained using the coincidence condition between the two scintillators labeled as “1\textsuperscript{st} layer” and “2\textsuperscript{nd} layer” in Fig. 5.3. Shown on the right are the corresponding simulation results of 350 MeV protons thrown isotropically. The solid and dotted histograms are the results of simulations with Geant4 and Geant3 (using the VMC package), respectively. The experimental results are calibrated to the Geant4 simulations at high peaks.

since it is built up by those events which effectively pass through one layer of iron placed right before the “2\textsuperscript{nd} layer”; the peak of the “1\textsuperscript{st} layer” is built up by events which essentially pass through the first iron layer before being registered by the “1\textsuperscript{st} layer”. The reason that we do not see the small peak of the “2\textsuperscript{nd} layer” in the data should be due to the misalignment of the iron-scintillator layers resulting in a geometry slightly different from what we implemented in the simulations (Fig. 5.3).
5.4 Detection of target recoil particles

In the feasibility experiment we used different detector elements in order to study different reaction channels by installing them at appropriate positions. This way, we could detect various interaction products such as the light ejectiles and the projectile-like particles by (at least) partly covering the predicted phase space of the expected interactions. In order to study the elastic scattering channel of proton-$^{136}$Xe a UHV-compatible single-sided silicon strip detector of 1 mm thickness preceded by a 1 µm thick foil of nickel was installed inside the target chamber (see Fig. 5.2). Using the data from the first group of strips of the Si-strip detector, the $^{136}$Xe($p,p$) elastic scattering differential cross section was determined. Since the registered data by the silicon detector (including the first group) comprises the elastic as well as inelastic scattering events, the most appropriate way of studying the elastic scattering channel would be to separate elastic from inelastic events by a precise determination of energy and angle. While the energy resolution was sufficient, the relatively bad angular resolution due to the target extension did not allow such a procedure. Therefore, for the investigation of elastic scattering, only data from the first group of strips were considered because here primarily elastic scattering events are expected, since the inelastic scattering cross section is expected to be negligibly small at angles covering this group of strips. The solid angle coverage of the first group of strips can easily be calculated from Fig. 5.8 to be about 15.4 msr. Inelastic reactions can also be studied in other strips where the cross sections and kinematics allow this.

5.4.1 Elastic scattering cross section

The elastic scattering cross section could be measured knowing that the first group of the Si detector is thick enough to effectively stop the elastically-scattered protons. This can be confirmed through simulations by calculating the deposited energy of elastically-scattered protons in this group (a thickness of 1.0 mm for the detector can stop protons of 12.1 MeV energy). Fig. 3.4 (bottom panel) shows the energy of the elastically-scattered proton versus its scattering angle. It is convenient to make use of the Mandelstam variable $-t$, which is defined as the square of the four momentum transfer. For the proton-$^{136}$Xe elastic scattering one can measure the cross section as a function of $-t$, which is expressed in terms of the proton scattering angle $\theta_p$ in LAB, as follows (derivation in A.2):

$$-t = 4 (cp_{CM})^2 \left( \frac{1}{1 + (\gamma_{LAB})^2 \tan^2 \theta_p^{LAB}} \right).$$

(5.1)

It is also possible to express $-t$ in terms of the proton kinetic energy $K_p^{LAB}$ after collision with the heavy ion:

$$2m_p K_p^{LAB} = 2 (cp_{CM})^2 \left( 1 + \cos \theta_p^{CM} \right) \equiv -t,$$

(5.2)
5.4. Detection of target recoil particles

in which \( m_p, K_p^{LAB}, \) and \( \theta_p^{CM} \) are the rest mass of the proton, kinetic energy of the recoil proton in the LAB frame, and scattering angle of proton in the center-of-mass frame (with its z-axis along the beam direction), respectively. In order to determine \( -t \) from the recoil energy \( K_p^{LAB} \) (since the angular resolution was not good enough), the energy of the protons was corrected for their energy loss in the nickel foil which was mounted in front of the Si-detector. For a \(^{136}\text{Xe}\) beam energy of 350 MeV/nucleon, the parameters \( q_p^{CM} \) and \( \gamma^{LAB} \) are obtained to be 0.8779 GeV and 1.3695, respectively. Figs. 5.12 and 5.13 show the experimental differential cross section (solid squares) as a function of \( -t \), obtained using Eq. 5.2 after correcting for the energy loss in the nickel foil and assuming that the recoil protons would not punch through in the first group of the Si-detector. The curve shows the prediction of the Glauber multiple-scattering theory for the elastic scattering cross section \([52, 11]\), assuming a matter radius of 4.9 fm. For comparison, the simulations for point-like and extended interaction profiles are shown as well. The simulations were performed by implementing the geometry in a Geant4/VMC code. Exploiting the VMC package allowed us to compare the Geant3 and Geant4 simulation results. We started from the Glauber theory for the elastic scattering cross section (solid curve) and used it as the generator for the elastic scattering channel. There is a cut-off in the simulations for the point-like target (asterisks in the top panel of Fig. 5.12) at about \( -t = 0.0067 \) (GeV/c)^2 which corresponds to the maximum scattering angle with respect to 90° in LAB at which a proton can be generated at the target point and still end up in the first group of silicon strips. In the absence of a threshold (which is 500 keV in the present experiment), the simulation points should, in principle, start to show up from about \( -t = 0.0001 \) (GeV/c)^2, which corresponds to protons generated with kinetic energies of about 70 keV.

In Fig. 5.12 (bottom panel), the shape of the simulations for the extended interaction profiles agree reasonably well with the experimental results up to a value of about \( -t = 0.011 \) (GeV/c)^2. However, beyond this value of \( -t \), there is an abrupt drop in the number of counts which is not compatible with the trend at lower \( -t \) values. This might have to do with the operation of the Si-detector in this experiment. Fig. 5.13 compares the Geant4 simulation results for two extended interaction profiles with the experimental data. The simulated data points start to show up at around \( -t = 0.0011 \) (GeV/c)^2 due to the energy threshold of 500 keV of the silicon detector. This is also visible in the experimental data points at very low values of \( -t \). The shapes of the simulations for the extended interaction profiles agree reasonably well (over the shown range of \( -t \)) with the experimental results; with the best agreement for a profile with a FWHM of 10.5 mm (stars) in the z-direction. Due to the small dimensions of the first group of the Si-detector and its placement close to 90° as well as the small extension of the interaction profile, (compared with its distance to the first group of silicon strips), the extension of the interaction profile along the x- or y-axis has a quite negligible effect on the shape of the simulations. This negligible effect was confirmed through simulations, even at the order of 1 cm for the FWHM_x or FWHM_y. This shows that the main source in shaping the slope
Figure 5.12: Top: solid squares show the experimental absolute elastic scattering cross section. The curves show the proton-\(^{136}\)Xe elastic scattering cross section as a function of four-momentum-transfer squared \(-t\) for a beam energy of 350 MeV/nucleon, as predicted by the Glauber theory [14] (solid curve) and Eikonal approximation (dashed curve [60]). The asterisks, which are normalized to data at \(-t = 0.0031\) (GeV/c)\(^2\), are the simulation results for the point-like target using the Glauber theory prediction. Bottom: the hollow squares and triangles are, respectively, Geant4 and Geant3 simulations (using the VMC package) which, together with the experimental data, are normalized to the theory curve at \(-t = 0.0031\) (GeV/c)\(^2\). The simulations for the extended interaction profile were done for an interaction profile of FWHM\(_z\) = 7.4 mm, using the Glauber theory.
5.4. Detection of target recoil particles

![Graph showing the relationship between \( \theta_{CM} \) and \( d\sigma/dt \) for different values of \(-t\).](image)

**Figure 5.13:** The curves and solid squares are the same as in Fig. 5.12 (top panel). Circles and stars show the simulation results, based on the Glauber theory (solid curve), for interaction profiles of FWHM\(_z\) = 7.4 and 10.5 mm, respectively. Hollow squares show the simulation results for the elastic scattering cross section, based on the Eikonal approximation (dashed curve), for an interaction profile of FWHM\(_z\) = 7.4 mm. The simulation data points (counts), obtained using Geant4, are normalized to the experiment at \(-t = 0.0031\) (GeV/c)\(^2\) and the error bars are statistical. \(K_{\text{LAB}}^p\) is the recoil energy of the proton in the laboratory frame and \(\theta_{CM}\) is the angle of the recoil proton in the center-of-mass frame with respect to \(-\hat{z}\), in which \(\hat{z}\) represents the direction of the beam.

of the count rates per \(-t\)-bin is due to its much higher sensitivity to the extension of the interaction profile along the z-axis rather than the other two axes. Nevertheless, the simulation results presented here are obtained using a full three-dimensional Gaussian profile as the position density of generation. For the four simulation results that are presented in Fig. 5.13, the Gaussian extension of the interaction profile along the \(x\)- and \(y\)-axes were assumed to be FWHM\(_x\) = 9.0 mm (corresponding to a target extension of 7.4 mm) and FWHM\(_y\) = 5 mm (since we had a beam diameter of 5 mm and since we expect no folding with target along the direction of injection of the gas-jet target, namely along the \(y\)-axis, with the assumption of a rather uniform target density in the interaction region). Along the z-axis the position distribution for generating protons was chosen according to a Gaussian of FWHM\(_z\) = 7.4 mm (circles and hollow squares) or FWHM\(_z\) = 10.5 mm (stars).

In order to deduce a cross section from the data, the experimental data points must be unfolded for geometrical effects by using appropriate correction factors. The
correction factors are inter-related to the geometrical acceptance of the first group of silicon strips and were calculated through simulations which will be discussed hereafter. In order to understand the descending behavior of the elastic scattering cross section, we can decompose the effects of various independent sources that have influence on the shape of the uncorrected cross section (solid squares in Fig. 5.13). The first source is the intrinsic shape of the underlying cross section. The other source is the geometrical acceptance of the Si-detector for which we expect, for the specific geometry in our experiment, that more particles miss the detector at larger values of \(-t\) (the effective solid angle is \(t\)-dependent).

One can calculate the acceptance of the detector for a particular scattering angle through simulations, provided that the interaction profile is well known. Thus, in order to study the effect of geometrical acceptance, we performed simulations for the recoil detector using an isotropic angular distribution for the generation of particles. Fig. 5.14 compares the correction factors that are obtained, using a uniform angular distribution, for the interaction profiles of FWHM\(_z\) = 7.4 mm and 10.5 mm. It is reasonable to use these correction factors (respectively, corresponding to the circles and stars in Fig. 5.14) in order to correct the experimental data and to compare them with any theoretical predictions. The results are shown in Fig. 5.15, where all the data sets are normalized to the theory at \(-t = 0.0031\) (GeV/c)\(^2\). It shows that the results corresponding to an interaction profile of FWHM\(_z\) = 10.5 mm agree best with the theoretical prediction. This fact could be interpreted as an indication of an asymmetric target profile with respect to the \(x\)- and \(z\)-axes. In case of a symmetric target profile with respect to the \(x\)- and \(z\)-axes, we would have a conical extension of the gas-jet which would be essentially symmetric around the \(y\)-axis (direction of the gas-jet injection). It should be mentioned that, in the simulations of Fig. 5.14, \(-t\) was calculated based on Eq. 5.2, since the effect of those few protons which punch through at areas close to the edges of the first group of the Si-detector was found to be negligible (see Fig. 5.18, top panel).

The effect of profile asymmetry discussed above is shown by simulations to be approximately the same as the effect of either a slightly rotated Si-detector around the target point or a shifted interaction profile along the beam direction. It is quite possible that the exact position of the Si-detector with respect to the nominal target point has not been determined very accurately in the experiment. Even if the position of the Si-detector during the experiment had been determined with a good accuracy with respect to the center of the scattering chamber, the center of the interaction region could have been easily off-centered by a few millimeters from the nominal position. The effect of an interaction point shifted by 1.5 mm toward \(-\infty\) in the \(z\)-direction yields a comparable correction factor, up to a few percent, to the case when we have a rotated Si-detector by about 0.5\(^\circ\) toward the \(z\)-axis (Fig. 5.14), and are both equivalent to an interaction profile of about 10.5 mm. Simulation results for the elastic scattering cross section, using an interaction profile of FWHM\(_z\) = 7.4 mm and a rotated geometry of 0.5\(^\circ\) (or a shifted geometry of 1.5 mm) would then also reasonably agree with the shape of the experimental curve.
Figure 5.14: Required correction factors for unfolding the acceptance of the first group of the Si-detector from the cross section, as obtained from simulations, using the uniform distribution. In the simulations we used the kinematics of proton-$^{136}$Xe elastic scattering. Circles and stars show the simulation results with FWHM$_z$ = 7.4 mm and 10.5 mm, respectively, as the extension of the interaction profile. Squares are obtained with an interaction profile of FWHM$_z$ = 7.4 mm, when the Si-detector is rotated 0.5° around the $y$-axis toward the $z$-axis and pluses are the results of a shift by 1.5 mm toward $-\infty$ in the $z$-direction, again with a FWHM$_z$ of 7.4 mm. Since in the simulations for the registered counts by the first group of the Si-detector all points are normalized to a constant (uniform distribution) at $-t = 0.0031 \text{ (GeV/c)}^2$, the correction factor is equal to 1 at this value of $-t$. In Fig. 5.13. This means that the interaction profile could still be the same as the one measured by the luminosity monitors (see Fig. 5.9). However, we cannot rule out the possibility of having extraordinarily extended target profile in the $z$-direction as the measurement of the luminosity was done through scanning the target with the beam in the $x$-direction. We could not disentangle the exact geometrical condition that we might have had during the experiment: a slightly rotated geometry with respect to the target point, a slightly shifted interaction profile with respect to the center of the interaction chamber, or an asymmetric profile). Nevertheless, based on simulations, the net result of the three scenarios would be the same as far as the elastic scattering cross section is concerned.

One can imagine other scenarios for the shape of the interaction profile than simply a Gaussian; especially when seeking an explanation for the abrupt drop in the cross section at $-t$ values higher than $-t \approx 0.011 \text{ (GeV/c)}^2$; see Fig. 5.12. It
could be that we had a non-uniform (and/or discontinuous) luminosity resulting from the non-uniformity of the target density over the area of interaction with the beam. In appendix B.1, we will try to understand the unusual behavior of the data points at higher $-t$ values merely based on a simulation analysis of different interaction profiles.

**Discussion**

Fig. 5.16 (top panel) compares the elastic scattering cross-section calculations for an interaction profile of FWHM$_z = 7.4$ mm for both cases when a uniform distribution or predictions of Glauber theory are used as the angular-density generators for the cross section. Clearly the difference between the two data points (related to the uniform and Glauber distributions) at each $-t$ reflects the deviation of the cross section from uniformity. Similarly, the amount of change in the difference between the two data points at $-t$ and $-t + \delta(-t)$ is directly related to the slope of the line connecting the two neighboring corrected points at $-t$. It is the slope of the fit to the corrected data points which would determine the local slope of the derived theory at a certain $-t$. Following the trend of the circles in this figure, we can intuitively conclude that, over the region of smaller CM scattering angles, the acceptance of
5.4. Detection of target recoil particles

The detector falls with \(-t\) (or equivalently with the energy of the scattered protons) faster than exponentially. Over the larger values of the CM scattering angle (away from 90° in LAB), the acceptance falls rather exponentially.

It is necessary to investigate the amount of contamination of punch-through events.
Figure 5.17: Top: simulations of the recoil detector, with 0.5 mm thickness for the Si-detector, showing four-momentum-transfer squared, calculated based on Eq. 5.2, versus the one calculated from angular relation (Eq. 5.1). The interaction profile of $\text{FWHM}_z = 7.4$ mm (corresponding to the plus signs in the bottom panel) is used in the simulations. Bottom: experimental data (solid squares) and simulation results of counts per $-t$-bin, in the proton-$^{136}\text{Xe}$ elastic scattering, as a function of four-momentum-transfer squared, calculated based on Eq. 5.2. The other three symbols represent the simulations for a Si-detector of 0.5 mm thickness with a uniform phase space density generator (the dotted line); stars: simulations with an interaction profile of $\text{FWHM}_z = 10.5$ mm, pluses: simulations with an interaction profile of $\text{FWHM}_z = 7.4$ mm, and triangles: simulations with an interaction profile of $\text{FWHM}_z = 7.4$ mm compensated for the punch-through protons. All experimental and simulated data points are normalized to the line at $-t = 0.0031$ (GeV/c)$^2$.

events in the results of the top panel in Fig. 5.16. This is because we established our arguments on the geometrical acceptance of the first group of the silicon detector based on the assumption of having negligible amount of punch-through events. For
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the interaction profiles of FWHM$_z$ = 7.4 and 10.5 mm (with FWHM$_x$ = 9.0 mm and FWHM$_y$ = 5 mm) the simulations show that majority of the generated protons stop in the first group of the Si-detector of 1 mm thickness (Fig. 5.16, bottom panel). The shaded region in this figure is due to those few protons which punch through at areas close to the edges of the first group of the Si-detector, where the amount of material through which the particles travel vary.

There is a possibility that we had an effective detector thickness of less than 1 mm for the silicon detector. In such a case protons might punch through the silicon detector, thereby changing the shape of the calculated elastic scattering cross section (based on Eq. 5.2). In order to have an estimate of this change, we can take an exaggerated case considering a thickness of 0.5 mm (half of the nominal thickness) for the silicon detector. Fig. 5.17 shows the results using a uniform distribution for the cross section and interaction profiles of FWHM$_z$ = 7.4 and 10.5 mm (with FWHM$_x$ = 9.0 mm and FWHM$_y$ = 5 mm). Up to $-t = 0.0085$ (GeV/c)$^2$ the simulated cross sections decrease smoothly; however, at higher values of $-t$, there are significant deviations from this smooth trend of the cross section. This has to do with those protons punching through the nickel foil and 0.5 mm thick silicon detector at high enough energies. Simulations show that, for the detector geometry in our setup, those protons that are generated at around $z = -5$ mm down to $-\infty$ can punch through the first group of the Si-detector. Based on this fact, we can compensate for the punch-through protons and extract the cross section. By incorporating the proper FWHM for the interaction profile into our simulations as well as normalizing the simulations to the statistics of our experiment, we can obtain a value of $-t$ which is now different from the one extracted through Eq. 5.2 due to the punch through; this is particularly important when we want to compensate for the punch-through protons in the experimental data. Therefore, by doing simulations with Glauber theory used as the generator for the cross section, we can repeat the same procedure as in the case of uniform distribution to see how much we need to compensate for the punch-through events in our experimental data. Fig. 5.18 shows the result of these simulations with an interaction profile of FWHM$_z$ = 7.4 mm and 0.5 mm thick Si. It confirms that the punch-through protons have negligible contribution in changing the shape of the elastic scattering cross section, calculated based on Eq. 5.2. Therefore, the probable minute deviations in the effective thickness of the Si-detector from 1 mm should not be any source of problems when making use of Eq. 5.2 to calculate the elastic scattering cross section. Therefore, unlike Fig. 5.17 (for the case of a uniform cross section and 0.5 mm thick Si-detector), it is not necessary to compensate for the punch-through events at all.

5.4.2 Acceptance correction by using the measured angular distribution

As already mentioned, one needs to correct for (i.e. unfold) the geometrical acceptance of the detector setup in order to obtain the correct elastic scattering cross
Figure 5.18: Top: same as Fig. 5.17 (top panel), using the Glauber theory as the generator for the elastic scattering cross section. Bottom: elastic scattering cross section obtained using Eq. 5.2 (dotted line; projection of the top histogram on the y-axis), contribution of the punch-through protons to the elastic scattering cross section (shaded area), and elastic scattering cross section compensated for the punch-through protons (solid line). All the histograms are shown for protons which punch through.

section that can be properly compared with theoretical calculations. In principle, one can correct the unfolded cross-section data using the correction factors obtained from simulations. In order to be able to draw any conclusion on the agreement between theory and experiment, we need to have another source to be used for our generator other than the theory under investigation. In subsection 5.4.1, we calculated the percentage of particles that are generated at a certain \( -t \) and missed the first group of the Si-detector (in a way, back-tracking the generated protons). This percentage was related to the geometrical acceptance of the detector at \( -t \) and subsequently provided the correction factor. In the following discussion we will try to reconstruct the underlying theory by using the measured position in the Si-detector.
and following a procedure that we will refer to as “trigonometric approach” in calculating $-t$. This will allow us to investigate the possibility of safely extracting the elastic scattering cross section, while making use of the position information of the Si-detector.

Fig. 5.19 shows the measured position in the Si-detector for the first group of strips close to 90° in LAB. Keeping in mind that we had a threshold of about 500 keV, one can understand the observed trend of data in this figure. Except for the last three strips, we can see an increase in the number of events registered at each position (strip), while getting away from the closest strip to 90° in LAB (the midpoints of the first and eighth strips of the first group of the silicon strips are placed at 89.3° and 86.5°, respectively). In principle, we would expect a decreasing behavior, since the elastic scattering cross section as well as the detector acceptance decrease with increasing $-t$ or equivalently with decreasing $\theta$. The fact that we see an opposite behavior in this figure (for the first few strips) has to do with the threshold condition which is discussed below.

**Figure 5.19:** Position information, as obtained during the measurement, of the detected events by all the eight strips of the first group of the Si-detector. The first peak is originating from the closest strip to 90°. The percentages on the figure reflect the relative heights of the peaks and sum up to 100%. The Si-detector had a threshold of about 500 keV.
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First, consider the situation where every strip receives equal number of elastically scattered events. Analytic calculations (trigonometric approach) show that for a target profile of FWHM$_z = 7.4$ mm, the energy threshold is directly related to the relative heights of the position peaks. Considering a Gaussian interaction profile with 9 mm, 5 mm, and 7.4 mm as the FWHM along the x-, y-, and z-axes and allowing the generated events at a specific random point to end up uniformly over the area of every strip, we can obtain the corresponding distribution of $-t$ for each strip. We expect identical peak heights for all the strips when we have no threshold, since we are assuming identical number of events ending up at every strip and triggering the detector. On the other hand, when we have a non-zero

![Figure 5.20: Trigonometric calculation (reconstruction) of $-t$ for the elastic scattering, based on Eq. 5.1, as seen by each strip of the first group of Si-detector. A Gaussian of 9.0 mm, 5 mm, and 7.4 mm as FWHM along the x, y, and z-axes is considered for the spatial generation of protons and all the events (dedicated to a specific strip) are required to end up at a random point on the strip surface. No threshold is considered here and the same number of events are distributed over each strip. The percentage of events that, for each strip, can satisfy a threshold condition of 500 keV is written under the corresponding curve. The detected $-t$ by the first group is, in principle, the summation of all eight spectra of the individual strips (spectrum on the bottom right hand side).](image-url)
threshold every strip detects a different percentage of events ending up in them. The resulting spectrum for the triggered events by the strips would show no more peaks of identical heights. The peaks would have relative heights as 0.34, 0.5, 0.55, 0.64, 0.74, 0.85, 0.89, and 0.92 as compared to 1 (when we have no threshold). These numbers are simply the ratio of events with \(-t\geq 0.0011\) (GeV/c)² (for a threshold of 500 keV) to the total number of events for each strip. Fig. 5.20 shows the reconstructed \(-t\) as it is seen by each strip as well as the reconstructed cumulative \(-t\) seen by the first group of eight strips. For the first few strips, this resembles the rising trend of the heights of the peaks in Fig. 5.19. However, what we see in Fig. 5.19 is a combination of the discussed threshold effect as well as the effect of non-uniformity of the elastic scattering cross section. This non-uniformity can be quantified and integrated in the above approach for distributing events; it can be thought of as dedicating different number of events to each strip. Therefore, if we could somehow obtain the relative number of events (based on the real elastic scattering cross section) to be dedicated to each strip, then we would expect a resulting spectrum with relative heights identical to what we see in Fig. 5.19. In principle, we can attribute the effect of the relative (appropriate) number of events to the relative heights of the position peaks by doing the simulations. This should give the exact relative heights of the peaks provided that we implement the exact experimental conditions in the simulations (such as the spatial extension of the interaction profile and the precise position of the Si-detector). In addition to the exact experimental conditions to be implemented in the simulations, we need to know the underlying cross section based on which to generate particles. We can try to make sense of Fig. 5.19, based on the approximate geometrical information (such as an interaction-profile extension of FWHM\(_z\) = 7.4 mm, FWHM\(_y\) = 5 mm, and FWHM\(_x\) = 9.0 mm) and by considering a shear elastic scattering cross section based on the Glauber theory (or the derived cross section in subsection 5.4.1).

Fig. 5.21 shows the position information of the detected events by all the eight strips of the first group of the Si-detector, as obtained through simulations with the mentioned assumptions. Comparing the relative heights of the peaks in this figure (bottom panel) with the trend of the percentage of events that can satisfy the threshold condition for each strip in Fig. 5.20, we can qualitatively conclude that the increasing behavior of the peak heights in Fig. 5.21 for the first five peaks is due to the threshold condition. On the other hand, it is the decreasing elastic scattering cross section which counteracts and takes over the threshold action at higher \(-t\) values and appears as gradually decreasing heights for the other three strips. Considering the qualitative agreement between Fig. 5.21 (bottom panel) and Fig. 5.19, we may assume that the relative heights of the position peaks (or at least the rising and falling trend of the heights of the peaks) in Fig. 5.19 could mainly be attributed to the elastically scattered protons. Based on this assumption, we may extract the appropriate number of events for each strip from this figure and feed it in our random-generation model to obtain the cumulative elastic scattering cross section. The difference between experiment and simulations may then be explained,
Figure 5.21: Same as Fig. 5.19, but obtained through simulations, using the Glauber theory, with threshold energies of zero (top panel) and 500 keV (bottom panel). The percentages on the bottom panel could be compared with the corresponding ones on Fig. 5.19.

In the following we try to unfold, to some extent, the influence of the threshold in shaping the spectrum of Fig. 5.19 by making use of simulations. Considering the simulation results in Fig. 5.21, we can use the ratio of the heights of the peaks of the upper panel to the corresponding ones of the lower panel and use them to enhance (modify) the heights of the peaks in Fig. 5.19. Since this ratio only represents the amount of threshold influence we assume that it is irrelevant to the...
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Figure 5.22: Thick dotted and solid curves (trigonometric approach): same as Fig. 5.20 but with a threshold of 500 keV for the Si-detector and generating appropriate number of events towards each strip as extracted from Figs. 5.19 (dotted curves) and 5.23 (solid curves). Thin curves (energy deposition approach): counts per $-t$-bin for the elastic scattering obtained, alternatively, through the experimental analysis of deposited energy in each strip.

theory curve that we used (Glauber) as our generator. Therefore, we can directly use these ratios to appropriately modify the heights of the peaks of Fig. 5.19. In principle, we would expect the resulting spectrum to show a pattern similar to what we see in the simulations of Fig. 5.21 (top panel). Fig. 5.23 shows the enhanced (modified) spectrum of Fig. 5.19 through exploiting the simulations of Fig. 5.21 with the assumed threshold of 500 keV (solid bars) as well as assuming an optional threshold of 900 keV (dotted bars). In none of these two results we see a decreasing trend for the heights of the bars as one should expect from the elastic scattering cross section (like in Fig. 5.21, top panel). Different threshold values were used in the simulations in order to investigate the effect of threshold on the relative heights of the modified spectrum. Nonetheless, all of them show smaller heights of the peaks at least for the first strip(s) relative to the next neighboring strip(s). This could be an indication that the detector position must have been different; for instance, the
Figure 5.23: Modified spectrum of Fig. 5.19, exploiting simulations of Fig. 5.21 with the nominal threshold of 500 keV (solid bars) as well as assuming a threshold of 900 keV (dotted bars). Simulations show that, regardless of the threshold value, the relative counts of at least the first and second strips (with respect to the others) violates the trend that one should expect from the elastic scattering cross section. This could be an indication that this strip must have been (partly) outside the phase space coverage of the elastically-scattered protons. See text for details.

spectrum corresponding to 900 keV in Fig. 5.23 can be explained if we consider a geometry of the Si-detector in which the first strip of the first group is placed (at least partly) at an angle more than 90° in LAB. In fact, a rotated geometry of the Si-detector in Fig. 5.8 as much as 1° around the y-axis toward the x-axis can place the first strip at a slightly larger angle than 90° in LAB. Fig. 5.22 shows as well the cumulative cross section (thick curves), obtained like the dotted curves when feeding the statistics of 500 keV threshold of Fig. 5.23 (instead of Fig. 5.19) into the generator. Fig. 5.24 shows the cumulative cross section, obtained through the trigonometric approach, together with the Glauber theory prediction for the elastic scattering cross section, all normalized to the theory curve.

There is an inherent drawback in this method of calculating $-t$ from the angular placements of individual strips. It arises from the sizable extension of the interaction
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Figure 5.24: Elastic proton-$^{136}$Xe scattering cross section as a function of four-momentum-transfer squared. The solid squares are the experimental data (corresponding to the thin histogram in the bottom right panel of Fig. 5.22), as obtained through Eq. 5.2 assuming no punch through, and the curve is the Glauber theory prediction. Solid triangles: cumulative $-t$, as in Fig. 5.22 (solid thick curve). The hollow triangles are for when we exclude the events registered in the last two strips of the first group of the Si-detector, using the same approach that led us to obtain cumulative $-t$ in Fig. 5.22. All points are normalized to the curve at $-t = 0.0031 \text{ (GeV}/c)^2$.

As an example we can take two generation points, over the interaction profile, one at $z = z_0$ and the other at $z = -z_0$ which are located symmetrically with respect to the origin. Clearly, the generation probability for the two positions is the same, but that the two generated particles at these points both end up at a specific strip with the same probability is not true. In our analytic approach of calculating $-t$, it is not possible to implement this difference in the probability of ending up at a specific
strip for a particle generated at $z_0$ or $-z_0$. Therefore, the bigger the extension of the target profile the less precise would be the calculation of $-t$, when using the trigonometric approach. Thus, one has to be careful in following this approach to calculate $-t$, even when there is a high confidence in the spectrum of Fig. 5.19. For extended target profiles, along the beam direction, this method is the most inaccurate when the detector is installed near 90° in LAB. Hence, there is no way of precisely calculating the elastic scattering cross section around 90°, based on this approach, other than minimizing the target extension along the beam direction. Similarly, for other reaction channels, one cannot expect that installing detectors at angles close to zero in LAB could overcome this inherent problem of target extension, because then the calculation of $-t$ gets sensitive to the target extension along the $x$- and $y$-axes.

There is a possibility that the behavior of the Si-detector (appeared as a drop in the cross section pattern of Fig. 5.12) had been due to the operation of the last two or three strips of the first group. In such a case, the registered energy of the events by these defected strips cannot be used to calculate $-t$ from Eq. 5.2 and might instead contribute to cross section at lower values of $-t$ than what we expect from an elastic scattering event. In this case, we are not able to exclude these miscalculated events. However, that does not necessarily mean that the relative peak heights of the last few strips are wrong. If we assume that all of the eight strips of the first group of the Si-detector were triggering correctly (based on the threshold energy), Fig. 5.19 would show a correct pattern of triggering while at the same time the last few strips did not register the correct deposited energy spectrum. Thus, it is possible that this figure could still be used to extract the elastic scattering cross section as the underlying cross section. It is interesting to note that the behavior of (at least) the first strip in Fig. 5.23 undermines the applicability of this method in calculating the cross section over the whole range of $-t$ and one should, therefore, avoid using this method.

Fig. 5.24 compares the results of the analytic calculation of the cumulative $-t$ for the two cases of excluding or including the influence of the last two strips. As can be seen in this figure, apart from the overall shapes of the two calculated cross sections, the inclusion of the statistics of all the strips causes the slope of the cross section to deviate from the theory prediction; even if the pattern in Fig. 5.19 (and consequently in Fig. 5.23) can be considered as a true triggering pattern, there still could be considerable amount of inelastic scattering events in the last two (few) strips which can satisfy the threshold condition. The qualitative similarity of Figs. 5.19 and 5.21 cannot, quantitatively, rule out the significance of inelastic scattering events that were detected by the first group of the Si-detector. Hence, it would not be reasonable to take all the statistics under the peaks (especially the last few peaks) of Fig. 5.19 as having originated from elastic scattering events.
5.4.3 Inelastic scattering channel(s)

Using the spectra of the deposited energy in the Si-detector groups (see Fig. 5.8), one can also try to identify inelastic scattering events [61]. In general, these spectra comprise elastic and inelastic scattering events. One can build up the whole spectrum of the deposited energy (in a Si-detector group) by performing simulations for elastic as well as inelastic scattering. It is necessary to know what the dominant inelastic scattering channels are if we want to understand the shape of the experimental spectrum. The procedure would be to use the theoretical estimation for the dominant channels in the Monte Carlo simulations producing protons with appropriate energies and angles in phase space.

The calculation of the inelastic scattering channels in \(^{136}\text{Xe}\), that leads to the Giant Dipole Resonance (GDR) with an excitation energy of 15.2 MeV and a width of 4.8 MeV [62] has been performed, using the Eikonal approximation [60]. Fig. 5.25 shows the theoretical calculations for the proton-\(^{136}\text{Xe}\) elastic and inelastic scattering cross sections, based on the Glauber multiple scattering theory and the above-mentioned calculations for the Giant Dipole Resonance in \(^{136}\text{Xe}\) (Fig. 3.4 shows the kinematics for the relevant elastic and inelastic scattering channels). Fig. 5.26 shows the experimental as well as the simulation results for the deposited energy in all the operating Si-detector groups. In the spectrum of the deposited energy for the fifth group of the Si-detector we expect the lowest contribution from the elastic scattering events (compared to the other groups of the Si-detector). Whereas, based on the simulations results for this group, we see the highest contribution from the inelastic scattering events, as compared to the amount of inelastic scattering events registered in the other groups for the case of GDR in \(^{136}\text{Xe}\) with \(E_x = 15.2\) MeV. In the simulations of the GDR channel, we assumed the total GDR strength given by the microscopic calculations of [60] to be situated at the centroid value, in order to get an impression of what to expect. For the simulations in Fig. 5.26, we only considered the elastic and inelastic scattering channels and assigned equal number of events to the two channels to be generated according to their respective kinematics and cross section. In order to have a thorough investigation of the contribution of various reaction channels to the observed spectra, one needs to take into account all possible reaction channels. Apart from the elastic and inelastic scattering channels one can think of possible transfer reactions as well, \(e.g., (p,d)\) and \((p,t)\). However, based on the kinematical calculations for these two channels, one would expect no Si-detector exposure from these transfer channels (Fig. 3.4, bottom panel, shows the respective kinematics).

The inelastic scattering channels may be identified by analyzing the data originating from those groups of the Si-detector which are positioned farther from 90° in LAB. This is especially fruitful in distinguishing the elastic and inelastic scattering channels, since we expect a narrower distribution in the deposited energy for elastically-scattered protons as we move away from the first group. This is because for smaller laboratory scattering angles, almost all protons punch through the de-
Figure 5.25: Theoretical calculations for the cross section of proton-$^{136}$Xe elastic scattering channel (thin curve), based on the Glauber theory, and inelastic scattering channel of giant dipole resonance of $^{136}$Xe with the resonance energy of 15.2 MeV, based on a calculation using the Eikonal method \[^{60}\] (thick curve). The GDR strength used in this calculation exhausts 56% of the TRK sum rule. The numbers on the top horizontal axis represent the proton scattering angle in the center-of-mass frame with respect to $-\hat{z}$; the upper row of numbers is related to the inelastic scattering kinematics of proton-$^{136}$Xe with $E_x = 15.2$ MeV, whereas the lower one is related to the elastic scattering kinematics. The brick- and simple-shaded areas in the picture show, respectively, the covered region of the fifth group of the Si-detector by the elastic and inelastic scattering kinematics for a point-like target. The boundary edges of the two shaded areas correspond to the LAB scattering angles of $a = c = 73.4^\circ$ and $b = d = 76.6^\circ$.

The detector and deposit almost the same amount of energy in the detector. This narrower pattern of the deposited energy is clear in the spectrum of elastic scattering of the fifth group as compared to the fourth group in Fig. 5.26. If we did not have protons punching through these layers then we would expect a completely different behavior in terms of the extension of the elastic scattering spectrum in these groups. In this case, it is the kinematical curve of Fig. 5.27, rather than the straggling, that influences the amount of extension of the elastic scattering spectrum as shown in
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Figure 5.26: Deposited energy in the first and last two groups of the Si-detector as measured in the experiment (thick histograms) and obtained through simulations. In the simulations for the elastic (thin histograms) and inelastic (dotted histograms) scattering channels an extended interaction profile of FWHM$_z = 7.4$ mm is assumed and equal number of events were thrown into the phase space for both channels. In the simulations for the inelastic channel of $^{136}$Xe, a giant dipole resonance with $E_x = 15.2$ MeV is considered.

Fig. 5.26, top panel. Whereas, when we have punch-through protons, it is the kinematics of Fig. 5.27 as well as the energy of the protons that compete in determining the amount of extension of the spectra of the deposited energy. For instance, based on kinematics, this extension is broader for the fifth group as compared to the fourth
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Figure 5.27: Four-momentum-transfer squared versus the scattering angle in LAB for the proton-$^{136}$Xe elastic scattering. The scattering is in inverse kinematics with a beam energy of 350 MeV/nucleon. The shaded regions show the coverage of the four-momentum-transfer squared (and not the scattering angle) by the five groups of the Si-detector in the case of a point-like scatterer.

Fig. 5.28 shows the simulation results for the amount of GDR inelastic scattering events registered by the fourth and fifth groups of the Si-detector (rotated by 0.5° around the $y$-axis) for an interaction profile of FWHM$_z = 7.4$ mm. The reduction of the statistics, appearing at around 8 MeV in the second panel, is due to the minimum in the cross section pattern. Based on the results of the second panel, protons start to punch through the fifth group at energies around 12.1 MeV. Accidentally, around the same energy, the inverse kinematics of the two-body proton-$^{136}$Xe inelastic scattering (with 350 MeV/nucleon) requires the scattering angle to turn around (see the bottom panel of Fig. 5.28). This is due to the specific detector thickness in the present setup.

Fig. 5.29 shows the experimental data for the response of the fifth group of the Si-detector together with the simulation results of the elastic and inelastic (GDR) scattering channels for a point-like target as well as an extended interaction profile. In the simulations, the ratio of the elastic scattering to inelastic scattering events
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Figure 5.28: Top panel: simulation results for the deposited energy in the fifth (thick line) and fourth (thin line) groups of the Si-detector for the inelastically-scattered events corresponding to the GDR excitation of $^{136}$Xe with $E_x = 15.2$ MeV. Second panel: simulations for the kinetic energy of proton versus the deposited energy in the fifth group of the Si-detector for the GDR events. In the simulations, an interaction profile of FWHM$_z = 7.4$ mm and a rotated geometry by $0.5^\circ$ around the $y$-axis toward the $z$-axis is considered. Bottom panel: kinetic energy of proton after inelastic scattering versus the proton laboratory scattering angle, calculated using Eqs. A.9 and A.13. The numbers on the histogram show a few proton scattering angles in the center-of-mass frame corresponding to $\theta_{LAB} \approx 10^\circ, 20^\circ, 29^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ, 73.4^\circ, 76.6^\circ, 76.6^\circ$, and $73.4^\circ$. $P_1$ and $P_2$ represent the location of the edges of the fifth group of the Si-detector on the kinematical curve with the assumption of a point-like target. T represents the turning point of the kinematical curve. See text for further details.
Figure 5.29: Simulations and experimental results for the deposited energy in the fifth group of the Si-detector. The simulations are for the elastic as well as the inelastic scattering events for the giant dipole resonance of $^{136}$Xe with $E_x = 15.2$ MeV. The dotted curves show the simulations for the point-like target, while the solid curves are for an interaction profile with the spatial extension of $\text{FWHM}_z = 7.4$ mm, when the Si-detector is rotated $0.5^\circ$ around the $y$-axis toward the $z$-axis. The spectrum in the bottom right panel is the sum of the two spectra in the top panels.

is taken to be in agreement with the amounts of reaction rates observed by the Si-detector for the two reaction channels. Clearly, the extended tail in the experimental data is a sign of the extended target profile, as can be seen from the simulations. In the simulations of the elastic scattering channel, there is a step-like behavior right after the cut-off of the threshold region. It is due to those protons which punch through the fifth group of the Si-detector at regions close to the edges of this group. A large difference is seen between the results of the simulations ($\text{FWHM}_z = 7.4$ mm for a rotated Si-detector by $0.5^\circ$ around the $y$-axis toward the $z$-axis) and the experiment in the position of the peak from elastic scattering.

Assuming that we had a correct calibration for the experimental spectrum, one can think of other scenarios in order to reproduce this characteristic of the experimental spectrum through simulations, namely the position of the elastic scattering
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Fig. 5.30 shows the same results as in Fig. 5.29 (solid histograms), assuming a significantly smaller thickness of 0.5 mm for the Si-detector (or equivalently considering a not fully depleted detector). In this case, the simulations can reproduce data with the mentioned characteristic. However, we will also get a second bump close to the peak. In addition, the tail of the inelastic scattering events in the experimental data is more extended than in the simulations. Simulations show that whatever inelastic scattering channels we consider to have contributed in building up the tail of the experimental data, we cannot reconstruct the contribution corresponding to deposited energies more than $\approx 9$ MeV in this spectrum. This is because a 0.5 mm thick silicon detector is simply not thick enough to let protons deposit more than about 9 MeV in it.

In order to have a consistent picture explaining both the peak position and the end-point of the experimental spectrum, there must have been a combination of a problem with the calibration as well as a nonlinearity problem; the two effects, which are related to the calibration, can shift the experimental peak position toward the higher values of deposited energy and at the same time keep the end-point around the position that simulations predict. However, the problem of nonlinearity needs to be further investigated.

Figure 5.30: Same as Fig. 5.29 (solid histograms) but for a 0.5 mm thick Si-detector.
In reality there are more inelastic channels which contribute to the shape of the energy spectrum. Clearly, for comparison with a measurement where clear evidence for the various giant resonances is observed, a full simulation including their widths should be performed. Nevertheless, a clear evidence for the GDR is seen in the data. With this experiment, the feasibility of the EXL setup for reaction studies was shown.