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Technische Universität München

Precise Measurement of Nuclear Interaction Cross Sections

with R3B

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Abstract

Astrophysical observations of neutron stars (NS) provide rather precise data about the global properties of such unique and fascinating objects, e.g., the mass and radius. For the interpretation of this data and to gain a profound understanding of the inner structure of NS, it is essential to investigate nuclear matter under extreme conditions. A key instrument to describe nuclear matter over a wide density range is the equation of state (EOS). The radius and stability of NS are governed by the pressure of the highly asymmetric matter in the inside, which is defined by the so-called symmetry energy in the EOS. This quantity and especially its slope parameter L around nuclear saturation density are experimentally only weakly constraint so far.

A experimental attempt to constrain the L parameter is to measure the neutron-skin thickness of highly asymmetric nuclei since both quantities are directly correlated. One of the most established experimental methods to probe the nuclear density distribution is the measurement of total interaction cross section at radioactive beam facilities. A common method to describe integrated cross sections is the Glauber reaction model. In such a model, which includes realistic in-medium modification for composite nuclei, the only inputs are the experimental nucleon-nucleon cross sections and the density distribution of the projectile and target nucleus.

For a precise determination of the neutron-skin thickness of exotic nuclei, and thus to constrain the symmetry energy slope parameter, it is essential to quantify the uncertainty of the reaction model under ideal conditions.

This work provides a detailed summary of the precise measurement of total interaction cross sections of $^{12}\text{C} + ^{12}\text{C}$ collisions in the energy regime between 400 and 1000 MeV/nucleon. The underlying experiment was carried out as part of the commissioning of the R³B setup during the FAIR Phase-0 campaign at GSI. The present analysis of total interaction cross sections is based on a transmission measurement, where the numbers of incoming and non-reacted projectiles before and after the reaction target have been identified. The identification of the non-reacted ^{12}C poses a challenge to the experimental setup since the time- and rate-dependent detector efficiency, as well as the geometrical acceptance of the whole setup, have to be considered.

The presented cross sections was determined with a total experimental uncertainty down to 0.4 % and represent the most precise data currently available in this energy regime. The validity of the measurement and analysis method was confirmed by data from previous experiments. It was shown that predictions based on a realistic Glauber reaction model are in good agreement with the presented experimental results for low energy but overestimate them by around 2.5 % at higher energies.

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1 Introduction

1.1 Astrophysical interest

1.2 EOS

1.3 Glauber Theory?

1.4 QFS Theory in inverse kinematics

2 Experiment

The present commissioning experiment was performed in 2020 at the FAIR Facility at GSI (Gesellschaft für Schwerionenforschung) in Darmstadt (Germany). The GSI Helmholtzzentrum für Schwerionenforschung operates a unique accelerator facility for heavy ions and focuses on several cutting-edge research fields. These include:

1. **Nuclear Physics:** Studying the properties of atomic nuclei, exploring the forces that bind protons and neutrons, and investigating exotic nuclei far from stability.
2. **Hadron and Quark Matter:** Investigating the behavior of hadrons (particles made of quarks) and the state of matter under extreme conditions, such as those found in neutron stars or during the early universe.
3. **Atomic Physics:** Examining the structure and dynamics of atoms, including highly charged ions, to understand fundamental atomic interactions and refine quantum electrodynamics.
4. **Plasma Physics:** Creating and analyzing high-energy-density plasmas to simulate conditions found in stellar interiors and other astrophysical phenomena.
5. **Biophysics and Medical Research:** Exploring the effects of ion beams on biological systems for applications in cancer therapy, particularly using heavy ion therapy, and studying radiation protection for space missions.
6. **Materials Research:** Investigating the response of materials to high radiation doses to develop more resilient materials for use in various technologies, including nuclear reactors and space exploration.

2.1 GSI facility

The GSI Helmholtzzentrum für Schwerionenforschung located at Darmstadt has a long history of research.... tell something about the beginnnings, first really heavy elements found there.

The GSI Helmholtzzentrum für Schwerionenforschung GmbH was founded in 1969 (as "Gesellschaft für Schwerionenforschung mbH) looks back on a successful research history. In the time between 1981 and 2010 six new superheavy elements were discovered. In the medical research field GSI has developed advanced cancer therapy techniques using heavy ion beams which target tumors with high precision, minimizing damage to surrounding healthy tissues.

Along with those groundbreaking discoveries in research the facility at GSI has always been an inspiring source of drive for new technologies.

The key devices/apparatus which enable to carry out experiments with heavy ions at GSI are: important to mention: GSI is the only facility with heavy ions in the world. The starting point for the production of relativistic heavy ions at GSI is the ion source where ions are generated by stripping electrons off the shell of the atoms. Depending on the experimental needs the ion sources at GSI are able to produce ions of many different kinds of elements (up to Uranium).

On the first acceleration stage the stable primary ions are injected from the ion source into the UNIversal Linear Accelerator (UNILAC). On a length of 120 meters ions are accelerated up to maximum energy of 11.4 AMeV. The low energy beam is now injected into the ring accelerator SIS18 (Schwerionensynchotron 18). Here the ion beam is further accelerated up to 4.7 GeV/u (for protons) / 1 GeV/u (for Uranium). The magnets and the ultra-high vacuum ($\sim 10^{-9}$ Pa) keep the ions well on their circular path (SIS18 has a circumference of 216 meters). For the production of rare heavy isotopes the primary ion beam from SIS18 can be impinged on a light nuclear target, e.g beryllium, the so called production target. These secondary beams of radioactive isotopes can be either stored in the experimental storage ring (ESR) for later use or transferred to the FRagment Separator (FRS). The FRS as a high-resolution magnetic spectrometer is capable to precisely select specific isotopes and to forward the desired beam of exotic relativistic nuclei to the various experiments or direct it to the ESR for later use.

2.1.1 FAIR Project

The FAIR (Facility for Antiproton and Ion Research) situated next to the GSI will be one of the most complex and largest accelerator facilities in the world. The construction

of the superconducting ring accelerator SIS100 with a circumference of 1.1 km, storage rings and experiment sites begun in the summer of 2017. Commissioning is planned in 2025 (?). Early Science. Before the commmissioning of the ring accelerator SIS100 several prioritized experiments with large impact in the scientific world will take place in the newly built experimental halls, such as experiments with the R3BSetup in the High Energy Cave (HEC).

2.2 R3B Setup

The R3B (Reactions with Relativistic Radioactive Beams) experiment in Cave C at the GSI Helmholtz Centre for Heavy Ion Research in Germany is a cutting-edge research experiment focused on the study of nuclear reactions and structure using high-energy radioactive ion beams. The experiment aims to investigate exotic nuclei far from stability, offering insights into the fundamental properties of nuclear matter, nucleosynthesis processes, and the forces governing nuclear interactions. A schematic overview of the R3B Setup can be seen in Figure blabla.

The short living (neutron rich) isotopes are injected to the Cave C from the FRS, which preselects as mass spectrometer the isotopes of interest, and impinge on a fixed target. The R3B setup is designed for kinematically complete reaction studies. To fulfill this requirement the incoming ions are tracked and identified on an event-by-event basis by dedicated detectors in the FRS via time-of-flight and deltaE measurement techniques. Depending on the settings and composition of the incoming ion beam different type of reactions take place in the target area with a large variety of reaction products: heavy ions (as products from fission/spallation reactions), neutrons, light charged particles and gamma rays. For the detection of gammas and light charged ions from reactions with the target the dedicated CALIFA calorimeter (see more in section blabla) and various tracking detectors are installed in the target region. The GLAD (GSI Large Acceptance Dipole) magnet, located at the center of the Cave C, acts as mass spectrometer for the forward boosted charged reaction residues. The magnetic rigidity of the charged reaction residues is measured by a combination tracking detectors and a time of flight wall after the GLAD magnet. This allows to identify the charged reaction residues and their momenta. For the detection of the neutrons, not deflected by the magnetic field of the GLAD magnet, the new array neutron detector (NeuLAND) is positioned after GLAD on the zero degree line with the incoming ion beam.

The high flexibility of the R3B Setup, it can be operated with The combination of the large spectrum of incoming ion beams in a broad energy range provided by the FRS facility and the high flexibility of the R3B Setup with state of the art detectors for the

specific physics-studies of interest makes it to an attractive play-ground for experimental astro-physics.

2.3 Detector Setup in S444 Commmisioning Experiment 2020

The S444 Experiment (successor experiment of the FAIR Phase-0 program in 2019, ref to Lukas Ponnath Thesis) for the commissioning of the CALIFA Calorimeter in its final mechanical design took place in February 2020. The choice to operate with stable ^{12}C primary beam with four beam energy settings - 400/550/650/800 AMeV gave the opportunity to use it as preparation for the following up S467 experimental run with neutron-rich Ca isotopes as medium-heavy incoming beam. The detectors for positional tracking, charge identification and time measurement were provided by the SOFIA(Study on Fission with Aladin, make footnote that ALADIN was the predecessor or GLAD) collaboration. These detectors are optimized for fission experiments with medium to heavy reaction fragments. As for the S444 experiment with primary ^{12}C incoming beam no fission reaction with multiple heavy charged fragments is expected the Sofia detectors were adapted accordingly (e.g. only one of the four sections of the Twin-Music Ionisation chamber was operated, see more in chapter Twin).

For this commissioning experiment most detectors and parts of the setup were operated in air. The target chamber was evacuated by gaseous helium at room temperature as well as the GLAD magnet. The fact that the ions interact with particles in air causes angular straggling in the flightpath reconstruction and can limit the resolution of reconstructed momenta from the reaction on the target[1].

2.3.1 Multi Wire Proportional Chambers (MWPC)

The positional tracking of the incoming ions as well as the charged reaction products were performed by using Multi Wire Proportional Chambers (MWPC). A MWPC operates on the principle of proportional counters that are arranged side by side in a plane, thereby providing spatial resolution for particle radiation. The multi wire proportional chambers were developed in late 1960s by George Charpak¹ at CERN[2].

The MWPC operates in the same way as aligned proportional counters with the difference of not having dividing walls between the anode wires. This reduces the material budget, hence improving the spatial resolution and reducing reactions with the detected particle.

¹George Charpak received the Nobel Prize in Physics in 1992 for his invention and development of particle detectors, in particular, the multiwire proportional chambers.

In the general design the MWCP is made up of a plane of anode wires enclosed between two cathode planes which are aligned parallel or vertical to the anode wires. Depending on the beam conditions the anode wires are set to high voltage (~ 1100 V) while the cathode planes are grounded.

The volume between the two cathode planes is filled by a gas mixture of 84% Argon and 16% CO₂. The decision of the gas mixture is driven by a balanced ratio between amplification and quenching properties of the gas.

When a charged particle passes through the detector it ionizes the gas. Primary electrons are created followed by a secondary ionization via electron avalanche. The electron avalanche drifts towards the wires (anodes) while the positive ions drift towards the grounded cathode planes. As the MWPCs are operated in the proportional region, the number of created electrons/ions is proportional to the initial ionization. Instead of reading out the signal from the wires it is read out from the strips of the cathode plane. This improves the position resolution in case the cathode planes are aligned perpendicular to the wires. In case multiple (neighboring) strips give signal the signal distribution over the strips is analyzed and fitted to provide the position information.

In the R3B setup for the S444 experiment four MWPCs were installed:

1. MWPC0: right at the beginning of the beam entrance in Cave C, 184 cm upstream to the target position to detect x- and y positions of the incoming ions.
2. MWPC1: 88 cm downstream to the target for positional tracking in x and y of the outgoing reaction fragment
3. MWPC2: 154 cm downstream also for positional tracking of the fragment
4. MWPC3: after the GLAD magnet. The x position of this detector gives the information about the magnetic rigidity of the reaction fragment.

Despite having the same mode of operation, they slightly differ in their construction design and positional resolution. For the technical specifications of the individual MWPCs, see table 1. Still to do: put in plot with potential field of mwpc and one with crosssign charged particle.

2.3.2 Ionisation Chambers - R3BMusic/TWIM Music

For the S444 experiment at R3B two types of multi sampling ionisation chambers (MUSICs) were installed: the R3B MUSIC, centered 153 cm upstream to the target, and the TWIN-MUSIC, 132 cm downstream to the target. Like the MWPCs (see

Common MWPC Settings	
Gas	84% Ar, 16% CO ₂
Windows	Mylar®
Anode wires voltage	1100 V
Cathode planes voltage	Ground
Wire pitch	2.5 mm
Wire diameter	5 μm
Width of X pads	3.125 mm

MWPC0	
X pads	64 pads, vertically segmented into two equal parts
Y pads	64 pads, horizontally segmented (3.125 mm width)
Active surface	200 × 200 mm ²

MWPC1 & MWPC2	
X pads	64 pads, vertically segmented into two equal parts
Y pads	40 pads (5 mm width), horizontally segmented
Active surface	200 × 200 mm ²

MWPC3	
X pads	288 pads
Y pads	120 pads (5 mm width)
Active surface	900 × 600 mm ²

Table 1: SOFIA MWPCs - Technical specifications

2.3.1) the ionisation chambers are gas-filled detectors for tracking down charged particles. While MWPCs consist only of a few mm of active gaseous volume, the ionsiation chambers have an expanded gaseous volume which allows to make precise energy loss measurements from the ionisation process of the gas. The multi sampling ionsiation chambers consist of a cathode plane and an anode plane, consisting of multiple anode strips. When a charged particle crosses the chamber the gas gets ionized and the created electrons and ions are separated by the strong electric field. While the ions drift towards the cathode plane the electons move to the anodes where each anode is read out separately. Since the energy loss of the passing through particle is proportional to the square of its charge ($\Delta E \sim Z^2$) the signal from the anodes allow to precisely measure the charge of the particle. Moreover multi-sampling ionisation chambers measure the drift time of the electrons created during the ionisation process on each anode (com-

pared to one or more reference anodes). Assuming a constant electron drift velocity ($\sim 40\text{mm}/\mu\text{s}$) over the gaseous volume the time information of each anode signal can be used to reconstruct the x-position of the passing through particle).

R3B MUSIC

The R3B MUSIC, installed 153 cm upstream to the target, is used to measure both the charge of the incoming ion before impinging on the target and the angle of the particle's trajectory. The detector has an active gaseous dimension of 20 x 20 x 40 cm³, confined on one side by a cathode plane and on the other side by an anode plane consisting of 10 anodes (8 readout anodes and 2 screen anodes). For the technical specifications, see table 2.

Dimensions	
Detector dimension:	51 x 54 x 53 cm ³
Active dimension:	20 x 20 x 40 cm ³
Dimension of one anode:	20 x 20 x 5 cm ³
Dimension of one screen anode:	20 x 20 x 2 cm ³
Gas	
P75 (Ar 25%, CH ₄ 75%)	
Voltage	
Cathode (left to beam direction):	-(2 – 6)kV
Anode (right to beam direction):	+300V
Resoultions	
still to do!	

Table 2: R3B MUSIC - Technical specifications

TWIN MUSIC

The TWIN MUSIC is a double ionisation chamber with one central cathode plane and two independent drift volumes and anode planes on each side. Each of the anode planes consists of 16 anodes for readout plus two screen anodes. Furthermore each anode is again segmented into up/down which splits the detector into four dedicated sections. As the TWIN MUSIC is placed 132 cm downstream to the target it is employed to measure charge and angular direction of the outgoing medium-to-heavy fragments. The detector was in particular designed for fission experiments where two or more fission fragments are created. If each fragment is flying through one of the four sections (which is mostly the case due to momentum conservation rules) charge and angle of each fragment can be measured independently.

To fulfill the required permanence of the field in both extended gaseous volumes (of

dimension 11x22x40 cm³) a Frisch grid is located 3 mm from the anode planes. The Frisch grid is metal mesh grid that shields the anode from the movement of ions produced during ionization process in the chamber ensuring that only the electrons that reach the anode contribute to the signal. Additionally, the shielding of the anodes by the Frisch grid account for the fast rise time of the signal at the anodes which diminishes pile-up effects and makes the detector high beam-rate capable (up to 100kHz). Further technical specifications you can find in table (bla bla)

Dimensions

Detector dimension:	43 x48 x55 cm ³
Active dimension:	two halves each 11x22x40 cm ³
Distance central cathode - Frisch grid:	11 cm
Distance Frisch grid from anode planes:	3mm

Gas

CH4 [79%], Ar [20%] and CO2 [1%]

Voltage

Central cathode:	-(2 – 6)kV
Anode planes:	+600V
Frisch Grid:	+250V

Resolutions

$\Delta E/E$	< 5% FWHM, total < 2% FWHM
ΔX	< 40 μ m

Table 3: TWIN MUSIC - Technical specifications, see also [3]

2.3.3 Sofia Start Detector

The SOFIA Start detector is positioned right after the R3B Music ionisation chamber and gives a time reference for the incoming ion. It is a 1 mm thin scintillating plastic blade attached with a photo multiplier tube on each side. The scintillator light from excitation of the incoming ions produce a clear signal on both photomultiplier tubes used for the time measurement:

$$t_{start} = 0.5 \cdot (t_{left} + t_{right})$$

To shield the plastic detector from daylight it is wrapped in mylar foil (300 μ m thickness).

2.3.4 GLAD Magnet

The **GSI Large Acceptance zero degree superconducting Dipole magnet GLAD** sits in the center of the R3B Setup in the cave C hall¹. With an adjustable field integral up to 5 Tm it has a high acceptance range in magnetic rigidity which is crucial for the identification of highly asymmetric reaction fragments. The homogeneous magnetic field in GLAD allows to achieve momentum resolutions $\Delta p / p$ of 10^{-3} in combination with the dedicated tracking system.

The large opening angle of ± 80 mrad makes the GLAD magnet highly transmissive for evaporated or scattered neutrons in the reaction process which will be subsequently detected in the NeuLAND detector.

The default bending angle of the beam with respect to the beam line was set to 18° . Herefore the currents where adjusted according to the beam energy:

1. 400 AMeV beam: 1444 Ampere
2. 550 AMeV beam: 1778 Ampere
3. 650 AMeV beam: 1957 Ampere
4. 800 AMeV beam: 2223 Ampere



Figure 1: Upstream view of GLAD magnet in the center of Cave C after installation in February 2016. Picture from [4]

2.3.5 CALIFA Calorimeter

The **CALOrimeter for In Flight detection of γ -rays and high energy charged pArticles**, CALIFA, is one of the main detector components of the R3B setup. It surrounds the target area and covers the full azimuthal range and a polar angular acceptance from

7° up to 140° in the target region. The calorimeter serves for the detection of gamma rays in the energy region $100 \text{ keV} \lesssim E_\gamma \lesssim 30 \text{ MeV}$ and light charged particles, mostly protons, up to $E_p \lesssim 700 \text{ MeV}$. To fulfill the demands requested by the different experimental campaigns an energy resolution of $\frac{\Delta E}{E}(@1\text{MeV}) \sim 6\%$ in the gamma-ray energy regime $\frac{\Delta E}{E}(@100\text{MeV}) \sim 1\%$ in the proton range regime is required.

Geometry

The CALIFA detector is a highly segmented detector with more than 2500 CsI crystals installed in the final design. Since experiments in the R3B setup operate in relativistic kinematics both the incoming ions as well as the measured particles originating from reactions inside the source experience relativistic effects, more precisely the so called relativistic Doppler effect. The emitted gammas and protons are not isotropically distributed around the source region but are boosted in forward direction. Moreover, the energy measured in the lab frame is different from the kinetic energy in the rest frame of the incoming ion.

The relativistic Doppler effect has a huge impact on the geometric design and requirements of CALIFA. Therefore the detector was subdivided into three polar angle ranges²:

- $7^\circ \leq \theta \leq 19^\circ$ - CEPA (CALIFA Endcap Phoswich Array): The most forward segment consists of 96 CsI(Tl) crystals. Due to the aforementioned rel. Doppler effect this area will have the highest intensities and energies. For high beam energies most of the particles will not be stopped inside the crystal and will escape as "punch-throughs". Despite the "punch-through" ions deposit only a fraction of their kinetic energy (ΔE) in CALIFA it is possible to reconstruct the initial energy of the particle². In CEPA crystals with a length of 15 cm are used and cover each a polar angle of $\approx 2^\circ$. This finer segmentation in polar angular range has the benefit to compensate for the high rate.
- $19^\circ \leq \theta \leq 43^\circ$ - Intrinsic Phoswich (iPhos): In conjunction with the CEPA, the iPhos region forms a part of the CALIFA Endcap. The iPhos region is, same as for the CEPA, affected by high rates. Protons reaching this region have high kinetic energies ($E_{kin,p} \leq 600 \text{ MeV}$) and therefore a large fraction of "punch-throughs" are expected. In the iPhos region 480 CsI(Tl) crystals with a length of 22 cm³ are

²This is done by exploiting the distinct scintillation components of CsI, see more in chapter 5 of [6]

³To fully stop protons with $E_{kin,p} \approx 600 \text{ AMeV}$ crystals with a length of 60 cm would be needed.

Such long crystals would have multiple drawbacks: reduced energy resolution due to worse scintillator light transport, enhanced nuclear reactions inside the crystals and challenging demands on stability of

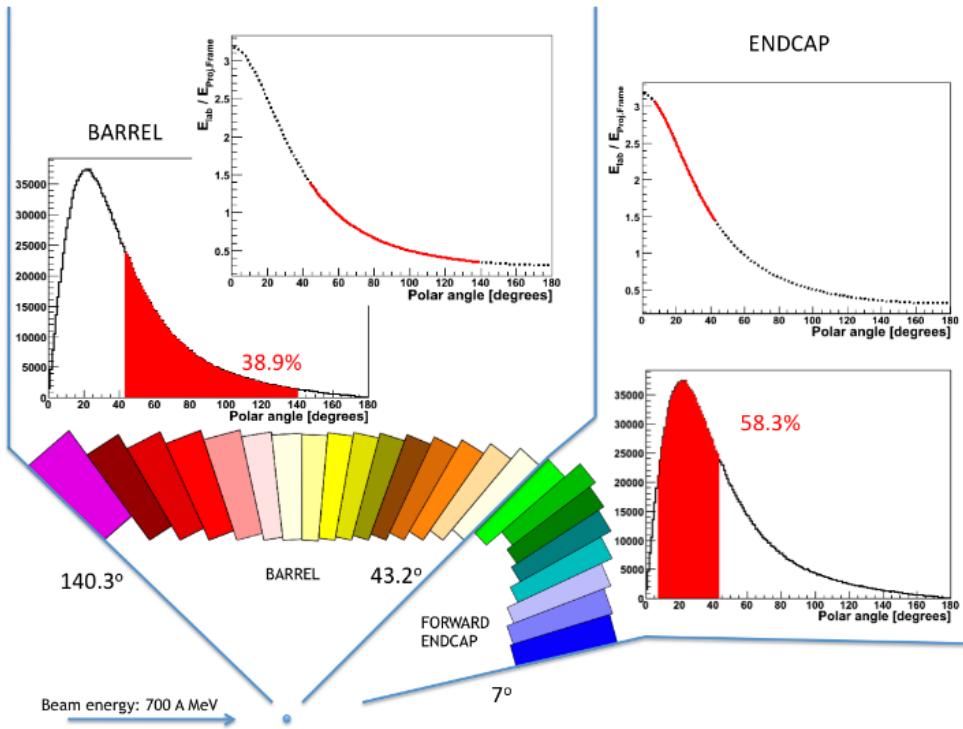
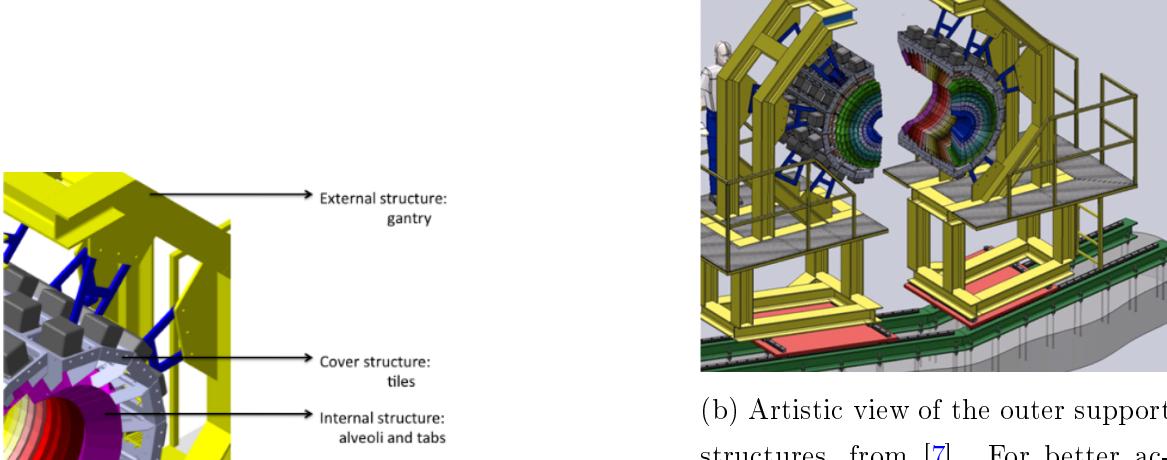


Figure 2: Schematic view of the Barrel and Endcap(iPhos and CEPA) segments of CALIFA and the according angular and energy distribution of emitted γ rays (monoenergetic in the projectile frame at beam energy of 700 AMeV). From [5]



(a) Zoomed view between inner and outer structure layers, from [5]. The black boxes symbolize the preamplifiers, which are directly mounted on the aluminium tiles.

(b) Artistic view of the outer support structures, from [7]. For better access to the target area the detector infrastructure is split into two halves, the left side commonly referred as "Messel" and the right side as "Wixhausen" (in-beam-view).

Figure 3: CALIFA internal and external holding structure

installed and cover each a polar angle of $\approx 3^\circ$. (For more information see Endcap TDR:[7]).

- $43^\circ \leq \theta \leq 140^\circ$ - Barrel: This segment covers the region where the lowest rates and energies are expected. The Barrel region contains 1952 CsI(Tl) crystals, due to the large polar angular coverage and the requirement of Doppler correction via angle measurement. The most forward crystals have a length of 22 cm (which allow to stop protons with $E_{kin,p} \leq 315\text{MeV}$). This length is reduced down to 12 cm for the most backward crystals (For more information see Barrel TDR:[5]).

The crystals are arranged in carbon fibre alveoli with a nominal wall thickness of 230 μm [5] that provide a support structure for the crystals and keep the material budget as low as possible. The alveoli in turn are held and covered by individual aluminium tiles. The volume enclosed by the alveoli and the aluminium tiles is flooded with nitrogen to keep humidity low on the surface of the crystals. For a sufficient suspension of the aluminium cover a robust external holding structure was designed.

In 2019 CALIFA was for the first time integrated into the R3B setup in form of the CALIFA demonstrator, a prototype consisting of seven mechanically separate petals, each of it containing a set of 64 crystals.

At the end of 2019 the CALIFA frame in its final design was installed and the forward

the detector holding structure

barrel part ($43^\circ \leq \theta \leq 90^\circ$ and full azimuthal coverage) was equipped with 1024 crystals.

For the S444 and the S467 experiment in 2020 CALIFA was equipped with 180 more crystals in the iPhos region ($19^\circ \leq \theta \leq 43^\circ$) which corresponds a coverage of 37.5 % in azimuthal angle for that region. Right before the S455 fissioning experiment [8] the full installation of the iPhos region was completed.

In February 2024 the full CEPA region ($7^\circ \leq \theta \leq 19^\circ$) with 96 crystals was commissioned for the first time together with a new equipped part of the backward barrel ($90^\circ \leq \theta \leq 102.5^\circ$, 128 crystals).

Energy and particle reconstruction with CsI scintillator crystals

Scintillator material, as caesium iodide doped with thallium (CsI(Tl)), is widely used in experimental physics to detect ionizing radiation from γ -rays or charged particles. The energy from the incoming radiation excites the electrons in the CsI crystal from their ground state to higher energy levels (excited states). The deexcitation, followed by photon emission (scintillation light), occurs via various complex mechanisms, not all of them completely understood yet (for more information see TODO:references!). The efficiency and properties of the scintillation process can be fine-tuned by doping CsI with small amounts of other materials, such as thallium. Thallium-doped Cesium Iodide produces light with a peak emission around 550 nm (green light) and has high light output⁴. The high density of CsI with 4.51 g/cm^3 makes it to an optimal scintillator material to efficiently absorb γ -rays and other high-energy particles. Moreover the CsI(Tl) crystal is well transparent to its own scintillation light, which is essential for the detection of the scintillator light. CsI(Tl) crystals are in addition relatively robust compared to other crystals and only slightly hygroscopic making them suitable for long-term use in experimental setups.

In a first approximation, the total amount of emitted light is proportional to the energy deposited in the scintillator. For γ -rays this is valid for $E_\gamma \gtrsim 400 \text{ keV}$ [10]. However, for charged particles significant deviations from linearity are observed, a so called "quenching" (TODO: add here more information, also the thesis of Max Winkel).

Although the energy calibration of CsI(Tl) crystals for charged particles is challenging, CsI(Tl) as such has the beneficial property of having a complex time dependent light emission consisting of two distinct exponential components. The time dependent light emission response of CsI(Tl) $L(t)$ can be approximated as:

$$L(t) = \frac{N_f}{\tau_s} \exp(-\frac{t}{\tau_f}) + \frac{N_s}{\tau_s} \exp(-\frac{t}{\tau_s}) \quad (1)$$

Where N_f is the amplitude of the fast component and N_s the amplitude of the slow

⁴The light output per MeV deposited energy in CsI(Tl), measured in [9], resulted in $5.2 \cdot 10^4$ (scintillation) photons/MeV.

component. Accordingly τ_f the life time of the fast component ($\tau_f \approx 650 - 770\text{ns}$) and τ_s the lifetime of the slow component ($\tau_s \approx 3.2 - 3.5\mu\text{s}$). It has been found that the proportion between the two components is energy and particle dependend. This property can be used to identify isotopes by extracting the N_f and N_s values from pulse shape analysis (PSA) on the according light emission response⁵. TODO: put in a picture of nf vs ns an one with the scintillation light impulse

From scintillator light to electrical signal

The scintillator light produced by the ionisation processes has first to be transported to the back-end of the crystal. The optimum design has been determined to be frustum-shaped crystals, wrapped into enhanced specular reflector (ESR) foil which provides excellent reflectivity. Finally at the backside of the crystals a large area avalanche photodiode (LAAPD) is attached⁶. Avalanche photodiodes have the same working principle as photodiodes to convert (scintillator) light into electricity. As a result of an additional highly doted p-layer a region with very high field is formed which accounts for amplification factors up to ≈ 100 .

For the next amplification step the electric signal is forwarded via thin ribbon cables to the back end of the preamplifiers from Mesytec[14] which can serve up to 32 input channels. For CALIFA two general types of peramplifiers are in use:

1. Dual Range (DR) Preamplifiers: They are used in the iPhos and CEPA region where both high energetic protons as well as gammas are expected. They cover two amplification ranges in parallel: the *gamma range* with low input signal and high amplification and the *proton range* with high input signal with low amplification. Following from this they have 64 channel differential signal output.
2. Single Range (SR) Preamplifiers: In the Barrel region, where mostly γ rays are expected, only one amplification range is needed. Depending on the experimental demands these preamplifiers can be switched to *gamma* or *proton range*. These peamplifiers have a 32 channel differential signal output.

The fall time for the preamplifiers τ_{RC} has been chosen to $\approx 35\ \mu\text{s}$. This is a trade-off between the ballistic deficit on one side (reduction of the signal amplitude due to low τ_{RC} , see also [11], chapter 3.4.5) and rate capability (restricted by large τ_{RC} value) on the other side.

The differential signal output of the preamplifiers is then transmitted over shielded and twisted line pairs to the input of the FEBEX Addon Boards (FAB) for further processing.

⁵The method has been implemented in the CALIFA Firmware as *QuickParticleIdentification – QPID*. For more information see [11] and [12]

⁶Detailed information about the crystal wrapping and LAAPD gluing can be found in this work:[13]

Signal Processing and readout system

The central hardware module for the signal processing in CALIFA is the FEBEX 3B Module (Front End Board with optical link EXtension[15]). Attached on it is a so-called AddOn board developed by TUM. The signal from the preamplifier gets here first filtered by a low pass two pole bessel filter ($f_c \approx 25MHz$). Furthermore, since the input of the FEBEX ADCs cover a range of ± 0.9 V while the signal output from the preamplifier only has one polarity, an offset to the signal is applied to use the full range of the ADCs. The signal from the ADCs is read out continuously on the FEBEX card and split up into two branches:

1. Fast/trigger branch: After being fed to a trapezoidal filter the signal is examined by three leading edge discriminators with configurable thresholds. Depending on the experimental requirements a coincident matrix between one or more discriminators and optionally external triggers validates the signal as event ready for data recording.
2. Slow branch: The validated signal gets delayed over a ring buffer and a pulse shape analysis is performed via various steps - signal decimation, moving average unit -technique, baseline subtraction and moving window deconvolution (MWD) - to recall the major steps⁷. From the resulting pulse shape pulse height measurement the energy deposited in the scintillator is determined. In addition the algorithm for the quick particle identification (QPID) is applied on the incoming signal which provides the fast(N_f) and slow(N_s) component of the signal for isotope identification and differentiation of stopped and punch-through particles. The CALIFA Firmware also allows to make time over threshold (TOT) measurements which is convenient for energy reconstruction when the incoming signals exceed the ADC range (which might happen when the preamplifier is set to *gamma range*)⁸.

Central hub for internal and external trigger forwarding are the Exploder modules[17]. The FEBEX crates are connected over an eight fold flat cable to the Exploder to the triggerbus. The trigger bus between the data acquisition PCs and the FEBEX cards is controlled by the TRIXOR card. This card sits inside the data acquisition PCs and is connected via ECL-lines to the Exploders and the PEXOR(PCIe Optical Link Interface) card via 26 fold flat cable. The PEXOR card is responsible for the data transfer

⁷A really detailed description of the pulse shape analysis in CALIFA can be found in Philipp Klenze's[16] and Max Winkel's thesis[12].

⁸The TOT energy-reconstruction method has the drawback of being really sensitive to pile-up events overestimating the energy deposition. Hence more suitable for regions with low event rates, such as Barrel region.

between FEBEX cards and the data acquisition PCs. It is connected via glass fibre cables to the FEBEX crates and stores locally in a 576 MB large RLDRAM (Reduced Latency Dynamic Random Access Memory) the data which consecutively gets transmitted via DMA (Direct Memory Access - data transmission speed up to 560 MB/s) to the RAM of the data acquisition PCs.

Since the Exploder provides various input and output lines and an internal switchable bypass matrix the CALIFA calorimeter can be operated as free running system with internal event validation only or by (additional) external validation. In case of internal validation only the signal from the preamplifiers has to exceed predefined threshold(s) to be accepted. This kind of configuration can be used for the purpose of calibration (with γ -ray sources like ^{22}Na or ^{60}Co) and expected low event rate experiments. For high event rates and event coincidence with other subdetectors additional external validation (e.g. clean CFD signal from START detector) is implemented.

To overcome dead time initiated by the readout/data transmission procedure each FEBEX channel allows to store up to 254 recorded events on the local memory. Each FEBEX channel has two available memory banks. Whenever one FEBEX channel reaches its preconfigured maximum number of events the full FEBEX crate is read out. To avoid dead time all channels force a memory bank switch thus allowing continuous dead time free event recording.

The Multi Branch System (MBS), developed at the GSI Helmholtz Center for Heavy Ion Research, is used on the data acquisition PCs. This software consists of several components that control and read out detectors, store the data, or forward it via various network protocols. The system also allows for the joint readout of multiple systems. For this, the trigger modules (TRIXOR) are connected via a special trigger bus to exchange trigger signals and dead time information. The triggered data is then collected, time sorted and cross-detector events are built by the dedicated MBS event builder⁹.

2.3.6 Sofia Time of Flight Wall

The Sofia Time of Flight Wall (or "Stop detector") is positioned at the very end of the experiment setup at approximately 6.6 m distance from the target position. It consists of a plane of 28 vertically aligned scintillator bars, each of dimension 32x600x5 mm. The scintillator plastics are numbered from 0 to 28 from left to right (when looking in beam direction). The time of flight of the ions between Start and ToFW can be measured by subtracting the time measurement of the Start detector from the ToFW. The combined resolution of the Start and TOFW detector is at 40 ps, for an average

⁹A more detailed explanation about the readout system and the critical FEBEX timing topic can be found in Philipp Klenze's thesis [16].



Figure 4: Sofia ToFW in Cave C, from [3]. Table 4: Sofia ToFW - Technical specifications

Plastic	EJ-232, no quencher
Plastic dimensions	5x32x600 mm ³
Detector dimension	5x900x600 mm ³ (28 plastics)
Photo-multiplier tubes	Hamamatsu 6533 and 10580
Total number of PMTs	56 (two per plastic - top and bottom)

time of flight of 30 ns[3]. For the technical specifications of the Sofia ToFW, see table 4 and reference [18].

2.3.7 NeuLAND Detector

For the detection of knocked-out or evaporated neutrons the **New Large-Area Neutron Detector (NeuLAND)** is installed at zero degrees after GLAD. In its final design it will consist of 30 double planes with 100 plastic scintillators of size 5x5x250 cm³ providing an active detector surface of 2.5x2.5 m² and thickness of 3m. Its high detection efficiency, a time resolution of $\sigma_t \leq 150\text{ps}$ and a mult-neutron efficiency of 50% to 70% for four-neutron events are crucial detector features for complete kinematics experiments at R3B. For more detailed information, see [19] and [20].

For the S444 commissioning experiment in 2020 eight double-planes of the NeuLAND detector have been used.

2.3.8 Calibration of the Detector Systems

3 Analysis - Total Interaction Cross Section $^{12}\text{C} + ^{12}\text{C}$ $- ^{12}\text{C} + ^{12}\text{C}$

This chapter will go through the analysis step by step from the unpacking stage to the final measurement of the total reaction cross section. It will start by a short overview of the transmission method used for the cross section measurements. The next step is the selection of clean incoming ^{12}C isotopes. Following the identification of the carbon isotopes after the target - for the measurement of the charge changing cross section - and as final step the reaction cross section measurement.

All relevant detector related geometrical and efficiency corrections will be addressed and their influence to the final result and its uncertainty will be discussed.

3.1 Cross Section Measurement via Transmission Method

In its most generic form cross sections give a measure of the probability that a specific reaction will take place when two or more particles collide. The cross sections measured in scattering experiments, as well as the energy and angular distribution of the reaction products, provide information about the dynamics of the interaction between the projectile and the target particle, i.e., about the shape of the interaction potential and the coupling strength.

The cross section σ can be derived by looking at the relation between the number of incoming particles (N_1) and unreacted particles after collision (N_2). For an experiment with fixed target with thickness z and volumetric number density n the number of reacted particles in the infinitesimal thin target layer dz can be expressed as:

$$\frac{dN_2}{dz} = -n\sigma N_2 \quad (2)$$

Solving this differential equation for N_2 (with the condition $N_2 = N_1$ for $z = 0$) discloses an exponential relation:

$$N_2 = N_1 e^{-n\sigma z} \quad (3)$$

Where nz can be summarized as N_t , the total number of scattering centers per unit area. The relation (N_2/N_1) , number of unreacted particles after collision versus number of incoming particles, is often called survival probability. For an idealistic experimental setup with full detector efficiency and no interactions in the setup material the cross section could simply be deduced from equation 3. To account for reactions of the projectile that occur within the setup material and first order detector specific distortions of output signals the survival probability (N_2/N_1) has to be divided by (N_2^E/N_1^E) , where N_1^E is the number of incoming particles and N_2^E the number of unreacted particles after

collision for an empty run respectively. The factor (N_2^E/N_1^E) can also be seen as an overall-experiment specific efficiency. The final formula for the cross section for a so called transmission measurement is:

$$\sigma = -\frac{1}{N_t} \ln\left(\frac{1}{\epsilon_{\text{setup}}} \frac{N_2}{N_1}\right), \quad \text{with} \quad \epsilon_{\text{setup}} = \frac{N_2^E}{N_1^E} \quad (4)$$

From the above formula 4 it is evident that for cross section measurements with the transmission method three types of observables have to be measured:

■ Number of scattering centers N_t

The number of scattering centers per unit area of the target is a target specific number. It depends from the target thickness and its density. The values herefore are taken from [21]¹⁰.

■ Number of incoming projectiles (^{12}C) N_1

For the measurement only events with well identified incoming ^{12}C projectiles are chosen. Herefore strict cuts on the detectors upstream the target are set. This strict (upstream) event selection makes sure that we only consider events with single ^{12}C ...See more in section 3.2.

■ Number of unreacted projectiles (^{12}C) N_2 after the target

Detectors downstream the target are used to count the number of unreacted projectiles ^{12}C . To reduce detector specific influences which could distort the result it is advisable to use only as few as requirable detectors for the clear identification of unreacted projectiles. Moreover detector specific efficiencies which only depend of the beam energy are cancelled out by including both empty and target runs in the cross section calculation, see equation 4. For all downstream detectors used in this analysis it is critical to limit any selection cuts to what is necessary and if necessary systematically check their effects on the counted number N_2 .

3.2 Event Selection

For event selection, all three upstream detectors are utilized: the MWPC0, the R3BMusic Ionization Chamber, and the START detector. To ensure a clean incoming event selection, the following prerequisites must be met:

1. ^{12}C identification of incoming projectile by upstream detectors:

In the S444 experiment the incoming beam was directly delivered by the SIS18

¹⁰For the purpose of this work the target thicknesses were remeasured at GSI with a chromatic sensor giving 2D depth profiles of each target.

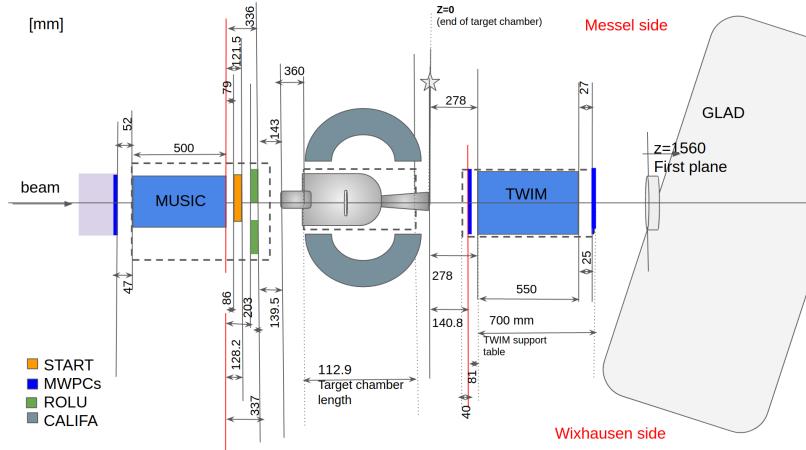


Figure 5: R3B Setup for the S444 experiment in the target region.

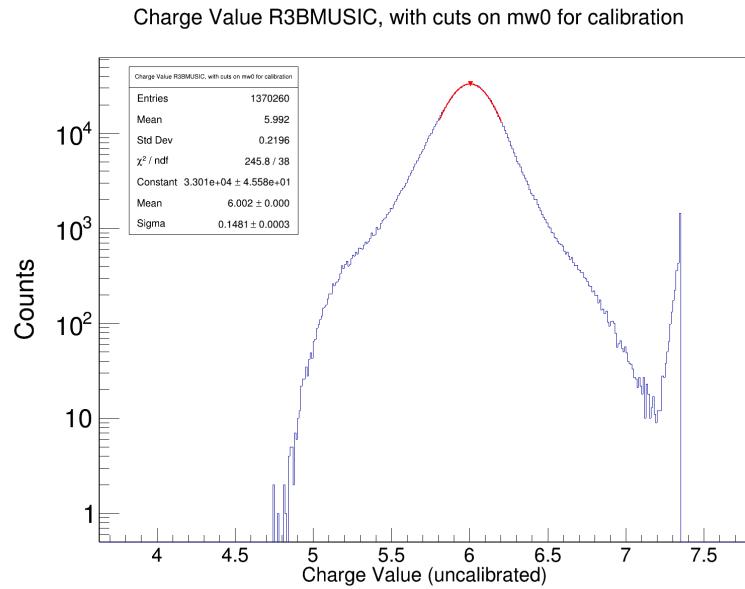


Figure 6: Charge distribution on R3BMUSIC with predefined calibration parameters with already applied positional cuts on MWPC0 - positioned upstream to the ionisation chamber.

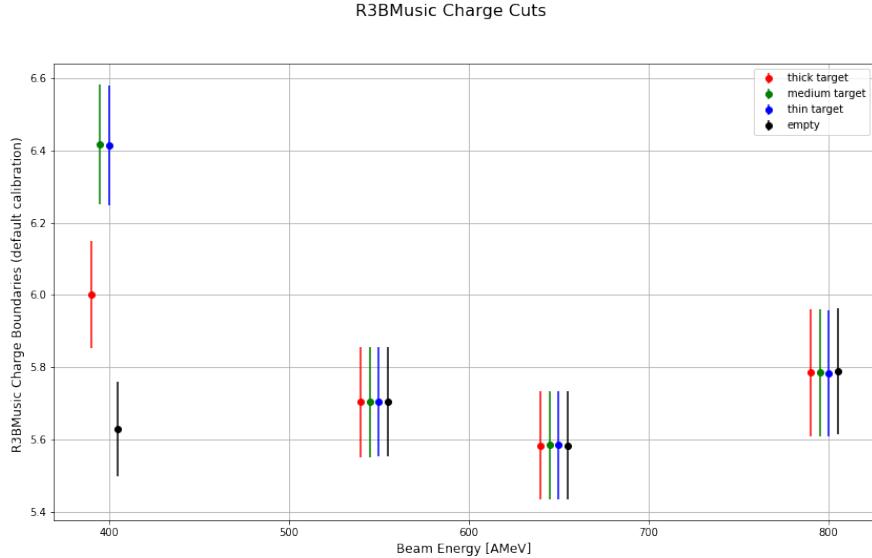


Figure 7: Strict $\pm 1\sigma$ charge cuts with R3BMusic for incoming particle selection. Fixed predefined calibration parameters were used which do not compensate different gain settings between runs.

ring accelerator, which is operated in ultra-high vacuum the level of pollution is low.(TODO:up to which stage do we have vacuum? Until MW0?)

For the charge identification of the incoming ion the R3BMusic ionisation chamber is used which is positioned directly after the MWPC0 at the beam entrance in Cave C,see figure 5. The R3BMusic detector measures anode-wise the energy loss of the passing-through ion which in the first order is proportional to the square of its charge ($\Delta E \sim Z^2$). Herfore the default predefined calibration parameters are used. Figure 6 shows the measured charge distribution in R3BMusic. To select $Z = 6$ incoming ions the distibution is fitted. All ions with charge within the $\pm 1\sigma$ range are accepted. Figure 7 summarizes the $\pm 1\sigma$ cuts on the R3BMusic charge for empty/target runs for all beam energies.

2. Pileup rejection and TPat selection:

The overall recoding and merging of the data from various subdetectors is one of the tasks of the Data AcQuisition (DAQ) system. Whether an event is recorded or not depends on the pre-established trigger logic. Various detectors can send out triggers to the main DAQ when certain conditions are given (e.g. CALIFA sends aout a trigger when a hit with more than 20 MeV is recorded). The different triggers are processed by the trigger logic and summarized as a defined trigger pattern, so called TPat, which is stored in a 16-bit mask for each event. Table 5 gives an overview of the trigger logic and the trigger patterns set in the S444

experiment. For this analysis the "*Min. Bias*" trigger is required¹¹.

Since the TPat selection itself does not necessary set any pileup constraints it

Bit Position	TPat Name	Description
0	Min Bias	Hit in Start detector
1	Reaction	"CalifaOR" -high energy hit in CALIFA
2	Neutron	Hit in NeuLAND
3	p+n	Hit in CALIFA and Neuland
8	Califa	high energy hit in califa - off-spill
9	NeuLAND	Hit in NeuLAND - off-spill

Table 5: List of TPats set for S444 experiment. As for the selected runs low beam rates ($< 10kHz$) were expected no dead time issues should arise for the in-beam detectors, therefore no downscaling of the *Min. Bias* TPat was deployed.

is important to analyse the signals of the detectors upstream carefully to insure yourself that only events with one incoming ^{12}C ion at a time get selected. Therefore events with incoming ions with charge $Z = 6 \pm 1\sigma$ are chosen, as discussed in the previous point. Moreover it is required that both left and right preamplifiers of the START detector have seen a coincident signal within a time-window of 1.391 ns. The overall searching window of the START detector was set to 2 μs . For the MWPC0 which is placed right at the beam entrance of Cave C no hit multiplicity cuts were applied considering its operating mode, which is designed for charge sharing between the readout pads.

3. Projectile's focus on the active target region:

To assure that the incoming ^{12}C ion hits the target it is necessary to select only events where the projectile is focussed to the active target region. Therefore strict cuts on the MWPC0 x and y positon are applied. This was achieved by fitting the x and y distribution of the MWPC0 (without any restrictions on it) by a gaussian function. The selection of good incoming events was then restricted to events with hits in MWPC0 within the $\pm 1\sigma$ region in the x and y position, see figure 9 and 10.

The MWPC0 x-position and the available projectile angle in the x-y plane from the R3BMusic is used to propagate the corresponding x-position on the target location to further check that the selected projectiles hit parallel to the z-position (= beam direction) the target and do only have a minimal incident angle, see figure

¹¹This includes also "*Reaction*" and "*Neutron*" TPat since these patterns contain also "*Min. Bias*" TPat as necessary condition.

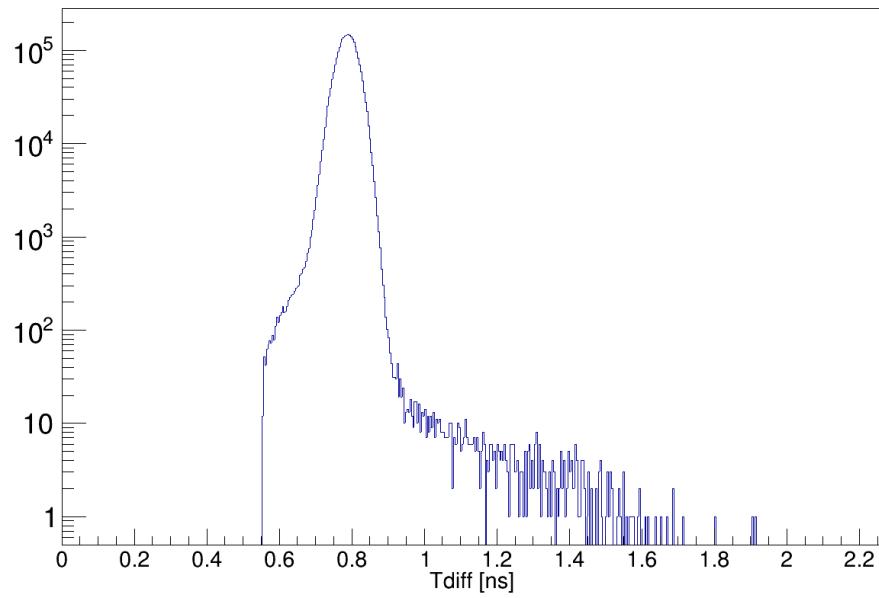


Figure 8: $\Delta t_{\text{right-left}}$ between hits in the Start detector for events with exactly one hit on the left and right preamplifier and limiting the time difference in the range 0.555 ns to 1.946ns.

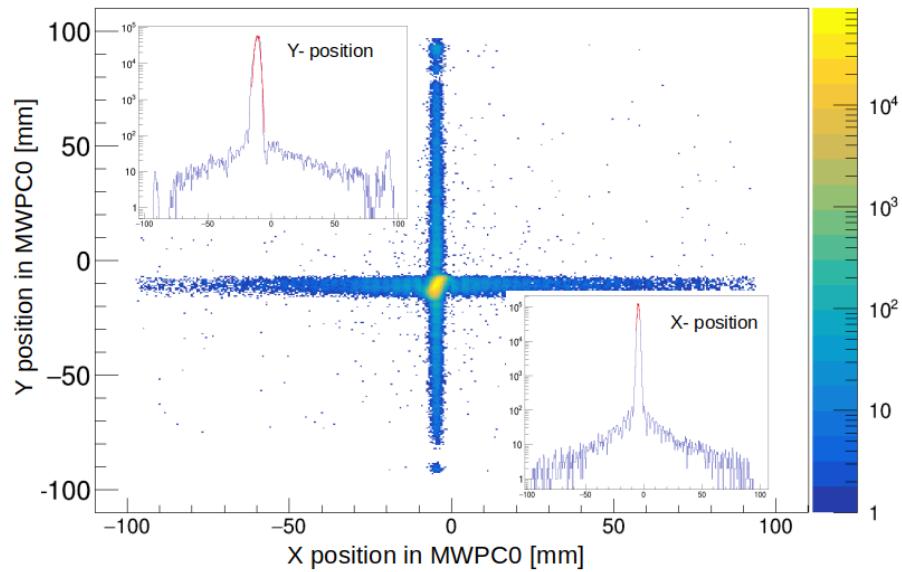


Figure 9: x-y position of incoming ion on MWPC0.

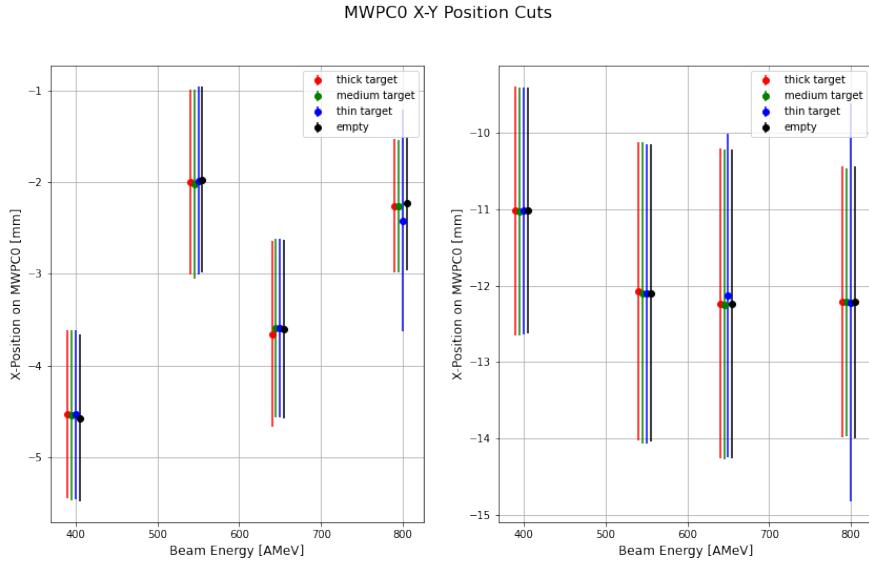


Figure 10: Overview of $\pm 1\sigma$ cuts in x and y in MWPC0 for empty/target runs.

11. This can also be seen as a consistency check whether the applied (predefined) calibration parameters are properly set.

3.3 Charge Changing Cross Section Measurement

The charge changing cross section refers to a measure of the probability that the incoming projectile will undergo a reaction inside the target that changes its charge. To measure the charge changing cross section it can be referred to formula 4 where in this case N_2 is the number of survived carbon isotopes, i.e. projectiles which did not change their charge state. For this measurement only the data from the double ionisation chamber TWIN (see section 2.3.2) needs to be read out and analyzed.

While for the event selection before the target the cut conditions can be arbitrarily strict (it will only have an impact to the statistics and the derived statistical error), cuts on the downstream detectors need to be avoided if at all possible. Too selective cuts on the identification of N_2 can distort the measurement.

3.3.1 TWIN MUSIC Calibration

For the analysis of data in TWIN MUSIC - different to the upstream detectors, where precalibrated data is used - the so called *mapped* raw level data is processed. In the mapped level TWIN MUSIC provides following information:

- **SectionID:** The detector is a double ionisation chamber and as such split up into four parts (in beam perspective): section 1 - right up; section 2 - right down;

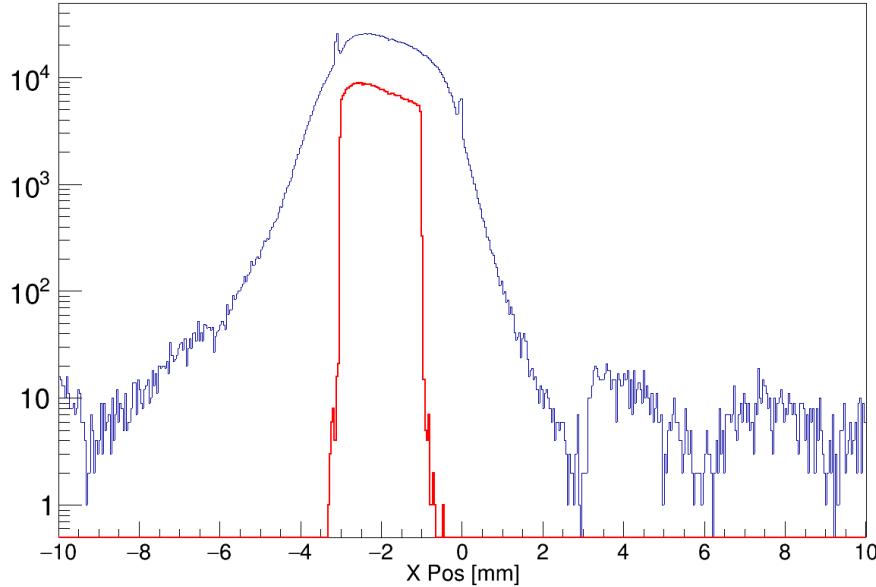
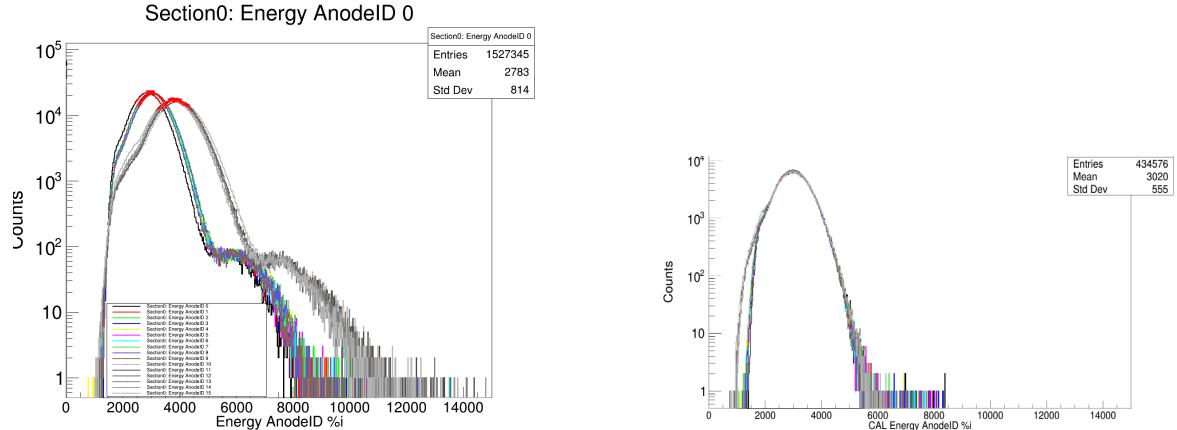


Figure 11: Propagated x-position on target location from measured x-value on MWPC0 and x-y plane angle measurement from R3BMusic. The active target area is 3 x 3 cm. In red the selected events with $\pm 1\sigma$ cut in x and y position in MWPC0, in blue all events.

section 3 - left down; section 4 - left up. For the S44 experiment only section 1 was operated and accordingly centered on the beam spot.

- **AnodeID:** TWIN MUSIC has 16 anodes for energy-loss readout and one reference anode (anodeID = 17).
- **Time:** Each hit in each anode gets assigned to a time. Each time has individually no meaning. The drift time (in ns) of the electrons from the ionisation process of the gas by the inflying projectile (or the fragments of it) to the anode is calculated by subtracting the individual anode time by the time of the reference anode. The reference anode gets its clean signal from a constant fraction discriminator of the START detector.
- **Energy:** Each hit in each anode gets assigned to an energy - except the reference signal. To reconstruct the charge of the crossing through charged particle anode-wise or detectorwise the parametrization formula $Z = [0] + [1]*\sqrt{E} + [2]*E$ is used.

The calibration of the TWIN energy for each anode is done run-wise. The event selection on the incoming ion is limited to the "Min. Bias" TPAT condition (coincident signal in START detector peamplifiers within 1.391 ns, on-spill). For the TWIN MUSIC only events where all anodes having exactly one hit (including the reference anode)



(a) Uncalibrated raw ΔE distributions for all 16 anodes for the 550 AMeV target run. The last six anodes have a slightly different electronics amplification chain.

(b) Gaussian fit applied to prominent peak and shifted to same position.

Figure 12: Fitting procedure in TWIN.TODO: nicer labeling!

are chosen. The most prominent peak ($Z = 6$) was fitted with gaussian function. The calibration was then done by determining the scaling factor for each anode that shifts the mean of the gaussian fits to the same position, see figure 12. For this analysis the peaks were shifted to $\Delta E = 6$. Since $\Delta E \propto Z^2$ holds, the scaled ΔE value, even though peaking at 6, is not equate the charge $Z = 6$.

3.3.2 TWIN MUSIC Event Selection

As previously stated cuts on the downstream detectors are avoided. However, events which have hits in one or several anodes in TWIN MUSIC but no signal in the reference anode are discarded as a whole neither contributing to N_1 (incoming selected ions) nor to N_2 (unreacted ions). If not reference time from START CFD signal is available it is not possible to measure the drift time in the individual anodes which makes it not possible to distinguish between signal and noise hits for multi-hit anode events in TWIN MUSIC. The number of events affected by this cut is in the region of few tens. This is negligible to the number of incoming ions N_1 and should not have any dependence whether the projectile reacted or not.

3.3.3 Carbon Identification

The identification of carbon isotopes in TWIN is done by reconstructing fragments with charge $Z = 6$ from 2D plots where coincident mean energy losses ΔE for different anode combinations are plotted. Since the TWIN MUSIC is multi-hit capable various

strategies were developed to deal with multi-hit events, i.e. when having anodes with multiple hits, decide which hit originates from the final state products from the reaction and which from background and noise.

The default strategy is to use the time information of each hit for selection. It has to be remarked that for the S444 experiment the TWIN MUSIC was read out by two independent MDPP modules[22]. The signals from the first reference anode and the first eight upstream anodes were forwarded to module 1, the ones from the last eight downstream anodes and the second reference anode were forwarded to module 2. For the first eight upstream anodes the drift time is calculated by subtracting the hit time in each anode by the reference time from the first reference anode and for the last eight downstream anodes accordingly the second reference anode was used:

drift time formula The time based selection algorithm for multi-hit anodes works as follows:

1. Get the mean drift time for the eight upstream anodes(t_{mean_up}) and the eight downstream anodes(t_{mean_down})¹². Anodes with multiple hits do not contribute to this calculation.
2. If there are anodes with multiple hits compare the hit time with the according mean drift time (t_{mean_up} for any of the eight upstream anodes, t_{mean_down} for any of the eight downstream anodes). Calculate herefore the absolute difference between mean drift time and each hit time:

$$\Delta t = |\bar{t} - t^i_{drift}|; i = \text{anodeID } (1-16) \text{ with } \bar{t} = \begin{cases} t_{mean_up} & \text{for } i \leq 8 \\ t_{mean_down} & \text{for } i \geq 9 \end{cases} \quad (5)$$

3. For each anodes with multiple hits select the hit with lowest drift time difference to the mean drift time.

After having selected the appropriate hit for single and multi-hit anodes the mean value for the pre-calibrated ΔE loss, see figure 12b, for the eight upstream and accordingly for the eight downstream anodes is determined. Finally, to select the number of survived carbon isotopes the mean ΔE of the eight upstream anodes versus the mean ΔE of the eight downstream anodes is plotted. To retrieve the number of survived carbon isotopes following two-dimensional gaussian fit is applied on the 2D plot on the charge $Z = 6$ blob,see figure 13:

$$f(x) = Ae^{-\frac{1}{2}\left(\left(\frac{x-\bar{x}}{\sigma_x}\right)^2 + \left(\frac{y-\bar{y}}{\sigma_y}\right)^2\right)} \quad (6)$$

¹²For the case all eight downstream anodes have multiple hits, set $t_{mean_down} = t_{mean_up}$ and vice versa

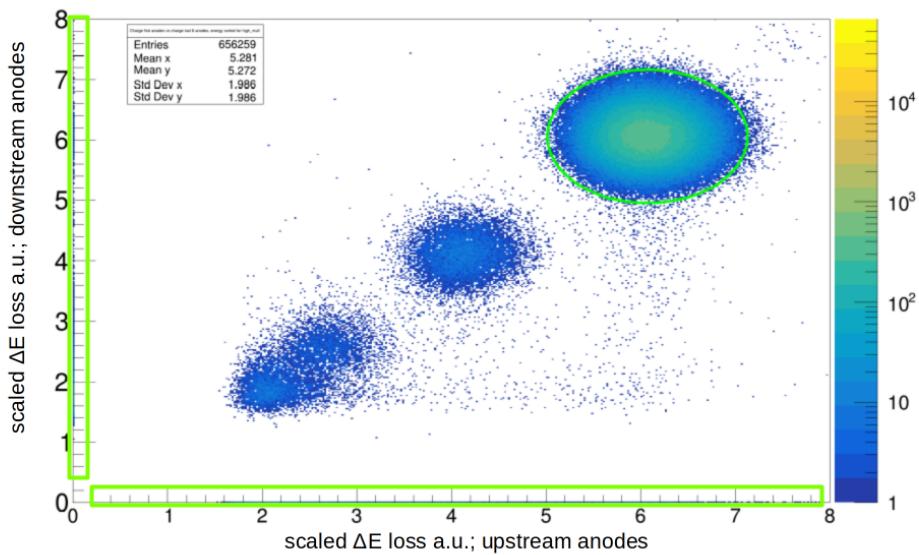


Figure 13: Two dimensional gaussian cut on identified carbon isotopes in TWIN MUSC. The horizontal and vertical side bars contain events where either the eight upstream anodes or downstream anodes have no hit entry.

, where x is the mean rescaled energy loss of the first upstream anodes and y the according eight downstream anodes. The number of survived carbon isotopes is given by the integral of events within the 2D gaussian fit. Since the anodes were read out by two independent MDPP modules with slightly different thresholds also events along the histogram axes with no hit entry in either the upstream anodes or downstream anodes are analyzed. For those events a one dimensional gaussian cut is applied using the parameters from equation 6. In figure blabla

3.3.4 Results

3.4 Geometric Corrections

3.5 Isotope Correction - Total Interaction Cross Section

3.6 Fine Tuned Geometric Correction

3.7 Results

3.8 qfs analysis

3.9 reaction cross section Analysis

4 Results and Discussion

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