



TUM School of Natural Sciences

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Precise Measurement of Nuclear Interaction Cross Sections

with R3B

Tobias Jenegger

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Vorsitz:

Apl. Prof. Dr. Norbert Kaiser

Prüfer*innen der Dissertation:

1. Prof. Dr. Laura Fabbietti

2. Prof. Dr. Lothar Oberauer

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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 hall². 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 ranges:

- $7^\circ \leq \theta \leq 19^\circ$ - 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

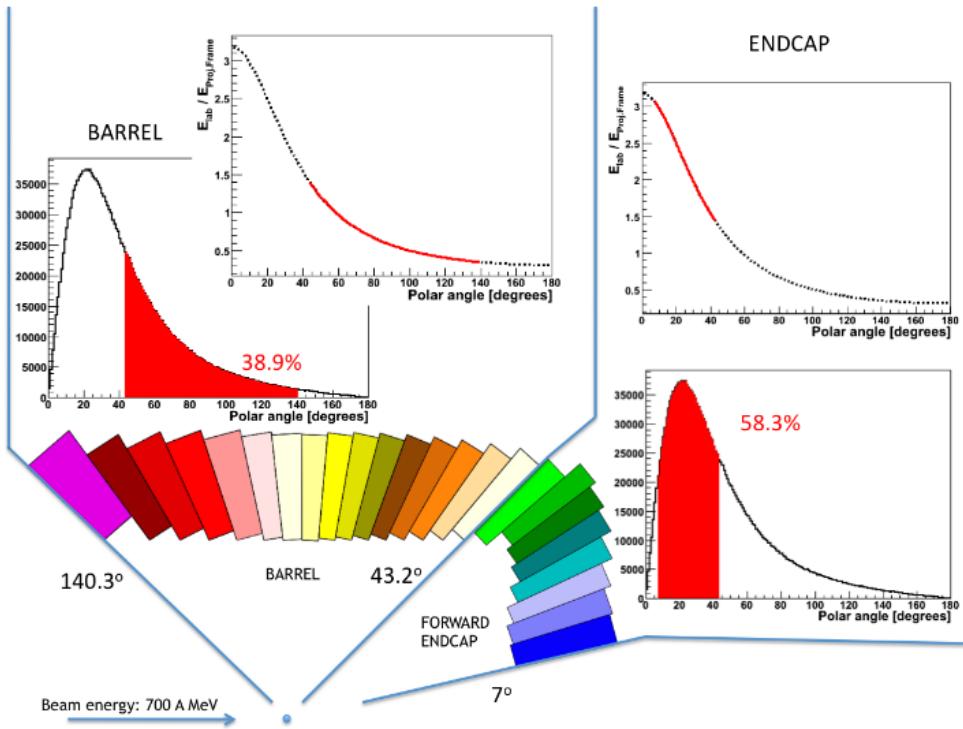
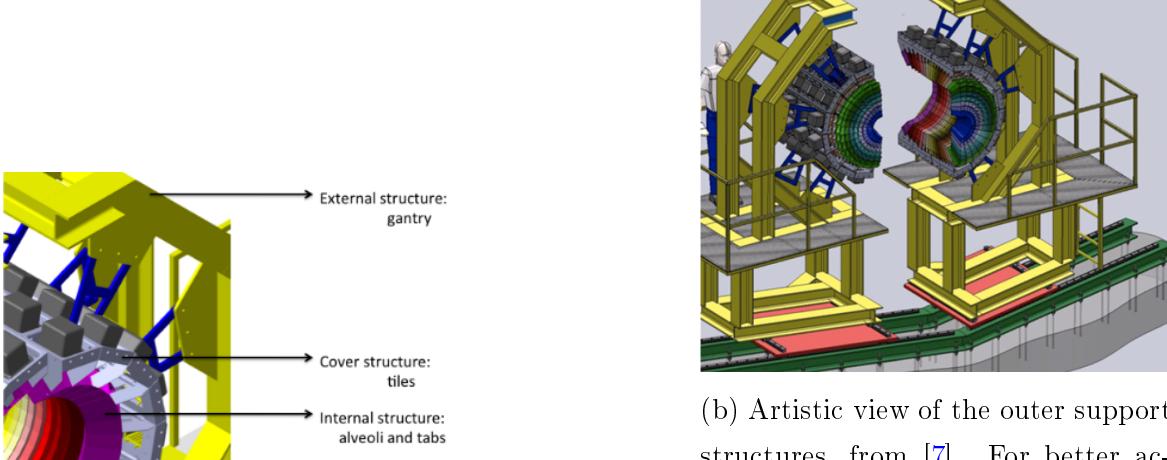


Figure 2: Schematic view of the Barrel and Endcap(iPhos and CEPA) segments of CALIFA and the according angular and energy distribution of emitted γ rays (monoenergetic in the projectile frame at beam energy of 700 AMeV). From [5]



(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 hold 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.

Energy and particle reconstruction with CsI scintillator crystals From scintillator light to electrical signal



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)

Signal Processing and readout system

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 time of flight of 30 ns[3]. For the technical specifications of the Sofia ToFW, see table 4 and reference [8].

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 [9] and [10].

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

3.1 qfs analysis

3.2 reaction cross section Analysis

4 Results and Discussion

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