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To cite this article: Kathrin Göbel *et al* 2020 *J. Phys.: Conf. Ser.* **1668** 012016

Coulomb dissociation of ^{16}O into ^{4}He and ^{12}C

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Abstract.
We measured the Coulomb dissociation of ^{16}O into ^{4}He and ^{12}C at the R^{3}B setup in a first campaign within FAIR Phase 0 at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt. The goal was to improve the accuracy of the experimental data for the ^{12}C(α,γ)^{16}O fusion reaction and to reach lower center-of-mass energies than measured so far.

The experiment required beam intensities of 10^{9} ^{16}O ions per second at an energy of 500 MeV/nucleon. The rare case of Coulomb breakup into ^{12}C and ^{4}He posed another challenge: The magnetic rigidities of the particles are so close because of the same mass-to-charge-number ratio $A/Z = 2$ for ^{16}O, ^{12}C and ^{4}He. Hence, radical changes of the R^{3}B setup were necessary. All detectors had slits to allow the passage of the unreacted ^{16}O ions, while ^{4}He and ^{12}C would hit the detectors' active areas depending on the scattering angle and their relative energies. We developed and built detectors based on organic scintillators to track and identify the reaction products with sufficient precision.

1. The fusion reaction ^{12}C(α,γ)^{16}O

The fusion reaction of carbon and helium to oxygen is key to understanding the evolution of stars and the relative abundances of both elements. The reaction rate of ^{12}C(α,γ)^{16}O has to be known with an uncertainty lower than 10% at a center-of-mass energy of 300 keV during Helium burning conditions. A direct measurement of the cross section ^{12}C(α,γ)^{16}O reaction in the astrophysically important energy region around 300 keV is very challenging because of the extremely low value of about 10^{-17} b [1].

Huge efforts have been undertaken to determine the ^{12}C(α,γ)^{16}O cross section over the last decades. Starting at higher energies, lower and lower center-of-mass energies were investigated. So far, experiments have studied the reaction down to about 1 MeV, e.g. [2]. Hence, only extrapolations of experimental data from higher center-of-mass energies to the astrophysical relevant energy region are available.

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2. Coulomb dissociation of ^{16}O

Indirect methods may bridge the gap towards the stellar energy regime. The Coulomb dissociation of ^{16}O is very promising and had first been suggested by Baur, Bertulani and Rebel [3, 4].

We measured the Coulomb dissociation of ^{16}O into ^{4}He and ^{12}C at the R^{3}B setup in a first campaign within FAIR Phase-0 at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt. The ^{16}O beam impinged on a lead target, where the ions could be excited in the Coulomb field of the lead nuclei such that ^{16}O would break up into ^{12}C and ^{4}He. A count rate of about 140 counts per hour was estimated at $E_{\mathrm{CM}} = 1$ MeV using a 50 mg/cm^2 lead target and a rate of $5 \cdot 10^9$ ^{16}O ions per second. This would allow to extract the ^{12}C(α,γ)^{16}O cross section with considerably reduced statistical errors, and even to extend the measured region down to about $E_{\mathrm{CM}} = 0.8$ MeV.

Nuclear breakup reactions from direct collisions have to be disentangled from the Coulomb dissociation. A beryllium target was used, which has a low Z compared to lead, since the target-charge dependence of the corresponding cross sections is very different. To understand this separation procedure and to investigate possible interference effects between the nuclear and Coulomb breakup we also used a third, intermediate-Z tin target [5].

3. The setup

The Coulomb dissociation experiment of ^{16}O required radical changes compared to the standard R^{3}B setup [6]: (1) The magnetic rigidities of the particles are so close because of the same mass-to-charge-number ratio $A/Z = 2$ for ^{16}O, ^{12}C and ^{4}He. (2) The high beam intensities of 10^9 ions per second could not be measured by our scintillation tracking detectors. Hence, all detectors had slits to allow the passage of the unreacted ^{16}O ions, while ^{4}He and ^{12}C would hit the detectors' active areas due to the scattering angle and their relative energies from the Coulomb dissociation reaction.

Figure 1 shows a sketch of our setup. The ions passed through two active collimators (ROLU) in front of the target to center and focus the beam during the beam setup phase. The CALIFA protoype around the target measured prompt γ-rays from excited ^{12}C fragments. The unreacted ^{16}O ions as well as the reaction products ^{4}He and ^{12}C were deflected in the superconducting magnet GLAD.

We used three pairs of scintillation fiber detectors to track the ions' trajectories. The detectors were mounted on linear drives to adjust the slits to the beam dimensions during the setup phase. The two fiber detectors between the target and GLAD are made of 200 μm square fibers and have an active area of 10x10 cm^2. They were designed and built at Goethe University Frankfurt. The four fiber detectors in the vacuum chamber connected to GLAD are significantly larger, they are made of 500 μm square fibers and cover an active area of about 50x50 cm^2. They were built at the detector laboratory at GSI Helmholtzzentrum. Figure 2 shows the fiber detector setups.

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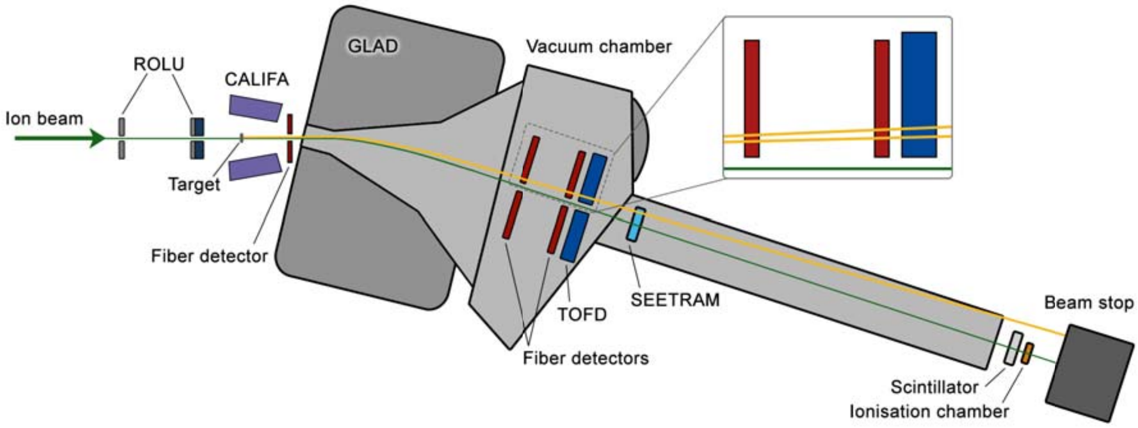

Figure 1. Experimental setup for the Coulomb dissociation of ^{16}O. The ions passed through two active collimators (ROLU) in front of the target to center and focus the beam during the beam setup phase. The CALIFA protoype measured prompt γ-rays from excited ^{12}C fragments. The tracking detectors - a pair of fiber detectors before the magnet GLAD and two pairs of fiber detectors and the time-of-flight wall ToFD behind GLAD - had slits to allow the unreacted beam to pass through while the breakup products would be detected. A SEETRAM [7] detector behind ToFD as well as a scintillator and an ionisation chamber at the end of the beam line measured the beam intensities. A beam stop was installed in the cave due to the expected high dose rate.

The ToFD detector measured the flight time and the energy loss of the ions, from which the charge Z can be determined. The detector consisted of two layers of scintillation bars, each 2.7 cm wide, 0.5 cm thick and about 1 m long. The first layer had 41 bars and an inner gap of about 8 cm, the second layer had 42 bars and an inner gap of about 5.5 cm. The layers are shifted by half a paddle, so that the paddles of the second layer cover the small gaps of the first layer and vice versa.

A SEETRAM detector behind ToFD as well as a scintillator and an ionisation chamber at the end of the beam line measured the beam intensities. The different intensity ranges of these detectors were used for a step-by-step calibration with 10^5 to 10^9 particles per second during the beam setup phase.

4. The first experimental campaign

4.1. A first look at the data

Figure 3 shows the calibrated charge number measured by plane 1 of ToFD as a function of the paddle number for a subset of the recorded data. All charges from eight to two are visible in the plot. The inner paddles receive a high beam rate, which smears out the charges. Paddle numbers 1 to 20 show higher count rates than numbers 24 to 44. Fragments from nuclear reactions have a lower energy than the primary beam and will therefore be deflected in the magnetic field to the side of ToFD with low paddle numbers.

Figure 2. Scintilation fiber detectors to track the reaction products. Left: Two fiber detectors with 200 µm square fibers and an active area of 10x10 cm^2. Right: Four fiber detectors with 500 µm square fibers and an active area of 50x50 cm^2 in the vacuum chamber connected to GLAD. All fiber detectors are mounted on linear drives to adjust the slits inbetween.

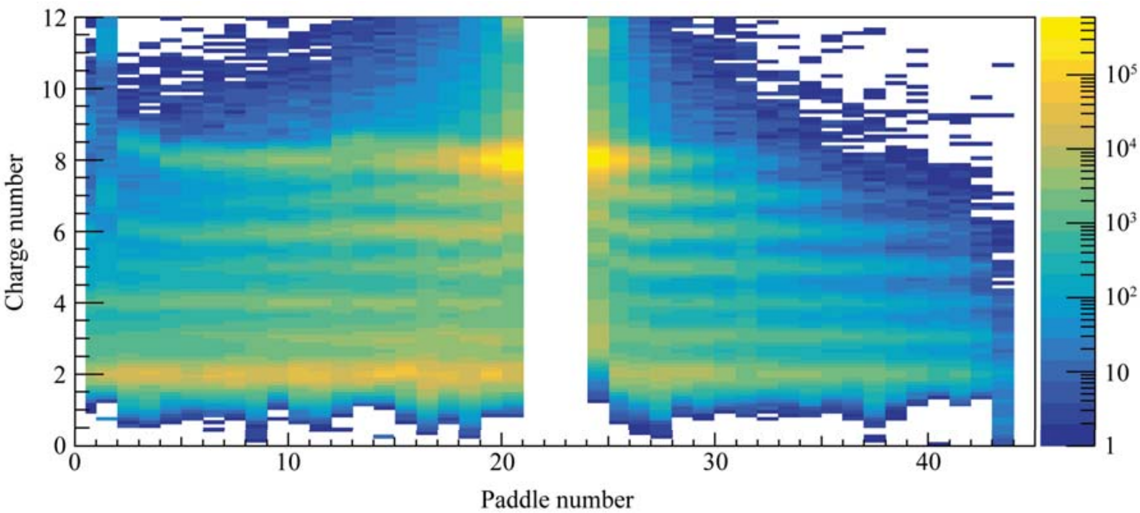

Figure 3. Charge number measured by plane 1 of ToFD as a function of the paddle number for a subset of the recorded data.

4.2. The beamtime

The first experimental campaign was carried out for six days in April 2019. Unfortunately, the accelerator could not reach the conditions desired by the experiment. The used extraction method of the synchrotron accelerator caused a micro-structure of the spills that resulted in high dead times of the data acquisition system. Overall, the statistics on tape is about a factor 20 lower than expected, which is especially problematic for reactions with very small cross sections at low center-of-mass energies.

Nevertheless, many events at higher energies were recorded, which will allow the

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validation of the Coulomb dissociation method and the comparison against results of previous direct reaction measurements. Future experimental campaigns will attempt to gather the necessary statistics to reach low center-of-mass energies of $E_{\mathrm{CM}} = 0.8$ MeV or lower.

Acknowledgements

This project was carried out within FAIR Phase 0 at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt. We thank the organizers and operators very much for their support.

This project was supported by the Bundesministerium für Bildung und Forschung (BMBF) (05P19RFFN1, 05P15RFFN1, 05P15RDFN1), HGS-HIRE, HIC for FAIR and the GSI-TU Darmstadt cooperation agreement.

I. Gašparić and R. Popočovski have been supported by the Croatian Science Foundation under projects no. 1257 and 7194.

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