# STUDY OF THE $^{15}$O$(2p,\gamma)^{17}$Ne CROSS SECTION BY COULOMB DISSOCIATION OF $^{17}$Ne FOR THE *rp* PROCESS OF NUCLEOSYNTHESIS*

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The $^{15}$O$(2p,\gamma)^{17}$Ne cross section has been studied by the inverse reaction, the Coulomb dissociation of $^{17}$Ne. The experiment has been performed at the GSI. The $^{17}$Ne excitation energy prior to decay has been reconstructed by using the invariant-mass method. The preliminary differential and integral Coulomb dissociation cross sections ($\sigma_{\rm Coul}$) have been extracted, which provide a photoabsorption ($\sigma_{\rm photo}$) and a radiative capture cross section ($\sigma_{\rm cap}$). Additionally, important information about the $^{17}$Ne nuclear structure will be obtained. The analysis is in progress.

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## 1. Introduction

X-ray bursts are one of the most fascinating places of explosive nucleosynthesis where proton capture reactions play an important role [1]. The X-ray burster is a binary system consisting of a red giant and a neutron star. It is characterized by a repeated sudden increase of X-ray emission, which is a consequence of a thermonuclear explosion ignited in the envelope of a compact and dense neutron star. In this system, neutron star accretes H/He-rich matter from the companion star. The accreted matter is heated and compressed, and the freshly accreted hydrogen and helium are ignited. Under these conditions, the break-out from the hot CNO cycles can occur via $\alpha$ capture reactions triggering first the $\alpha p$ and subsequently the $rp$ process. The $\alpha p$ process is a sequence of $(\alpha, p)$ and proton capture reactions up to the mass 40 region, and the $rp$ process is a sequence of proton captures and $\beta^+$ decays and produces the proton-rich isotopes up to the mass 100 region. The energy generated in this way can be observed as a peak in the luminosity curve in the X-ray spectral continuum. The trigger conditions for the burst depend on the efficiency of the breakout reactions from the hot CNO cycle [2]. The most possible breakout reactions of the CNO cycles are $\alpha$ capture reactions on the waiting-point nuclei ($^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ and $^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$) [2–4]. But, as an alternative, the two-proton capture reactions ($^{15}\mathrm{O}(2p,\gamma)^{17}\mathrm{Ne}$ and $^{18}\mathrm{Ne}(2p,\gamma)^{20}\mathrm{Mg}$) are also taken into account [5, 6]. In theoretical predictions, the direct three-particle capture process enhances the reaction rate of $^{15}\mathrm{O}(2p,\gamma)^{17}\mathrm{Ne}$ by a few orders of magnitude [6] compared with a sequential one [5]. Very important for detailed nucleosynthesis calculations are accurate experimental input parameters, *e.g.* cross sections, which allow to decrease uncertainties and clarify the situation. However, these cross sections are difficult to obtain experimentally, since the rp-process path lies along the proton dripline, and due to several particles in the entrance channel. The only way to measure such complicated reactions is the time-reversed process. In the present experiment, the $^{15}\mathrm{O}(2p,\gamma)^{17}\mathrm{Ne}$ reaction has been investigated by Coulomb dissociation of $^{17}\mathrm{Ne}$.

The proton-dripline nucleus $^{17}\mathrm{Ne}$ is also studied in the context of nuclear-structure physics. This Borromean nucleus is a promising candidate for a two-proton halo, due to a small $2p$ separation energy ($S_{2p} = 960$ keV) [7]. The mixture of the $d^2$ and $s^2$ configurations of the two protons outside the $^{15}\mathrm{O}$ core in the $^{17}\mathrm{Ne}$ ground state is still unknown, and predictions of the $s^2$-weight run from 15 to 70% [7–13]. The solution to this situation is an experimental determination of the $s^2/d^2$ mixture.

## 2. The experiment

In order to extract the $^{15}\mathrm{O}(2p,\gamma)^{17}\mathrm{Ne}$ cross section, the Coulomb dissociation method was used, which is usually employed to investigate the nuclear structure of exotic nuclei, and to study relevant reactions for nuclear astrophysics scenarios using an inverse process [14]. The experiment was performed at the GSI Darmstadt, using the LAND-R$^3$B detection setup. A sketch of the setup is shown in Fig. 1. The setup contains several detector types to identify and reconstruct the four-momentum of each particle on an event-by-event basis, by means of energy-loss, position, and time-of-flight measurements.

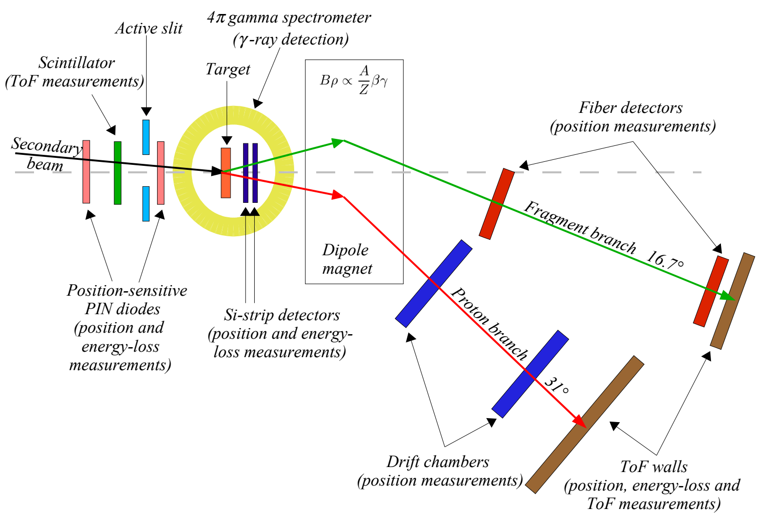


Fig. 1. LAND-R$^3$B experimental setup.

To produce the $^{17}$Ne secondary beam, a $^{20}$Ne primary beam was impinged on a Be target, situated at the entrance of the fragment separator (FRS), where dipole magnets filter out all species except those with a specific $A/Z$ ratio. The identification of the radioactive isotope $^{17}$Ne was made by a magnetic rigidity ($B\rho$), position and energy-loss measurements (position-sensitive PIN diodes), and time-of-flight measurements (scintillator detectors). The $^{17}$Ne, in this way, was successfully selected (Fig. 2 (I)).

The secondary beam, at an energy of around 500 $A$ MeV, then was directed onto the reaction target, which was placed at the center of a $4\pi$ $\gamma$-ray detector, to measure de-excitation $\gamma$-rays of heavy fragments. In order to investigate the Coulomb dissociation reaction, a $^{\mathrm{nat}}$Pb target (200 mg/cm$^2$) was used. To accurately subtract the background contribution and to properly estimate the nuclear contribution, several runs without target, and with

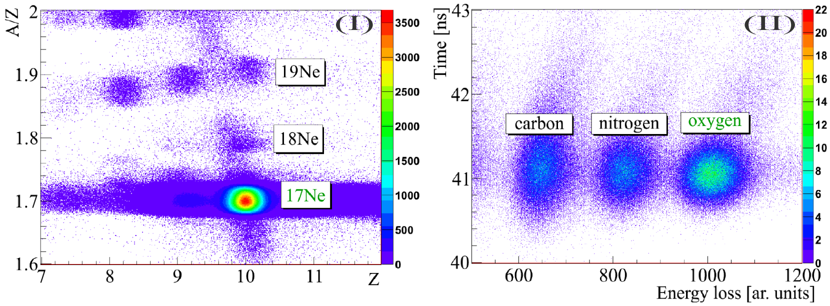


Fig. 2. (I) — The incoming beam nuclei; (II) — the outgoing fragments.

a $^{12}$C target were performed. Directly after the reaction target, two Si-strip detectors were placed to measure the energy-loss and positions of reaction products. The reaction products were separated according to mass and charge by the magnetic field of a large dipole magnet. After magnet, the two branches of detectors were used to measure the position, energy-loss, and time-of-flight of heavy ions (Fig. 2 (II)) and protons. To later reconstruct the excitation energy of the desired isotope, the invariant mass method was used. Next, the differential Coulomb dissociation cross section $\sigma_{\mathrm{Coul}}$ is obtained, which then, is converted into the photoabsorption cross section $\sigma_{\mathrm{photo}}$, with the virtual-photon theory. Finally, the radiative capture cross section $\sigma_{\mathrm{cap}}$ is obtained from the photoabsorption cross section $\sigma_{\mathrm{photo}}$, by means of the detailed-balance theorem [15]. For the proper cross section calculations, the data needs to be corrected for possible acceptance cuts along the beam line, the intrinsic efficiency of the proton detection in the drift chambers, and the $\gamma$-ray energy $E_\gamma$ for de-excitation $\gamma$-rays of the $^{15}$O fragment. In order to apply a realistic acceptance correction, the simulation package R3BROOT [16] was used, which contains full geometrical information about the setup, and allows to simulate fragment and proton behaviours. The intrinsic efficiency of proton detection was estimated by analyzing coincidences between the proton-branch detectors. The two-proton efficiency of these detectors was determined to be $55.9 \pm 1.5\%$. The required $\gamma$-rays were detected in the $4\pi$ $\gamma$-ray spectrometer. Two groups of $^{15}$O excited states were observed: above 5 MeV and 6 MeV. However, only 5% of the events show these excited states, which makes them negligible.

## 3. Preliminary results

The preliminary differential and integral Coulomb dissociation cross sections have been determined. To check the efficiency and the acceptance adjustments, two ways were used to calculate the integral cross section. First:

the cross section calculation purely from the $^{15}$O data gave $\sigma_{\mathrm{Coul}_1} = 289 \pm 32(\mathrm{stat.}) \pm 35(\mathrm{syst.})$ mb. The second approach: integration of the differential cross section spectrum, which gave $\sigma_{\mathrm{Coul}_2} = 256 \pm 15(\mathrm{stat.}) \pm 18(\mathrm{syst.})$ mb. The difference between these two values is 11%. The shape of the preliminary differential Coulomb dissociation cross section is in agreement with experimental results from Ref. [17] and with the theoretical predictions from Ref. [18]. The hypothetical and measured resonances are visible (Fig. 3). In the next steps, the photoabsorption and the radiative capture cross sections will be calculated.

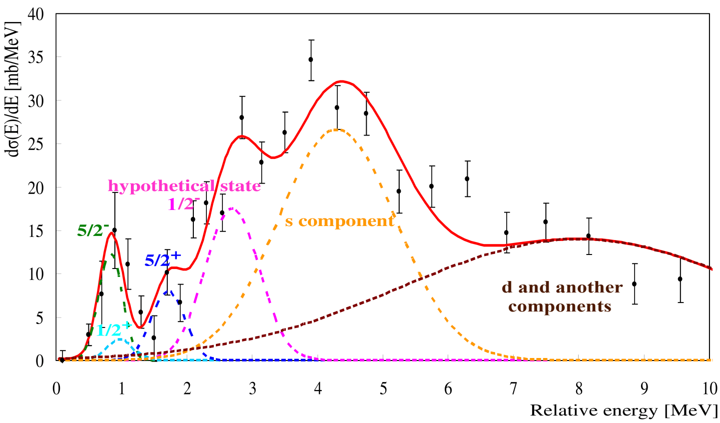


Fig. 3. The preliminary fitting of the hypothetical and measured resonances of the differential Coulomb dissociation cross section.

In order to extract informations about the three-body system (core $+p+p$), energy and angular correlations of internal clusters ([core, $p+p$] or [core$+p, p$]) in the Jacobi coordinates should be analyzed. Thanks to these comparisons, the mixture of the $s^2$ and $d^2$ configurations can be obtained [19]. The experimental data are convoluted with theoretical predictions provided by Ref. [20] using the simulation package R3BROOT. The final conclusion is not obtained yet.

## 4. Summary

A Coulomb break-up experiment of $^{17}$Ne was used to study the $^{15}$O$(2p,\gamma)^{17}$Ne cross section. The analysis of the shown data is ongoing and close to conclusion. The preliminary Coulomb dissociation cross section has been obtained. The photoabsorption and the radiative capture $^{15}$O$(2p,\gamma)^{17}$Ne cross section, as well as the $s^2/d^2$ mixture of $^{17}$Ne structure will be determined soon.

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