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Experimental study of the ^{15}O($2p$,γ)^{17}Ne cross section by Coulomb Dissociation for the *rp* process

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Abstract. The time-reversed reaction ^{15}O($2p,\gamma$)^{17}Ne has been studied by the Coulomb dissociation technique. Secondary ^{17}Ne ion beams at 500 AMeV have been produced by fragmentation reactions of ^{20}Ne in a beryllium production target and dissociated on a secondary Pb target. The incoming beam and the reaction products have been identified with the kinematically complete LAND-R^{3}B experimental setup at GSI. The excitation energy prior to decay has been reconstructed by using the invariant-mass method. The preliminary differential and integral Coulomb Dissociation cross sections (σ_{Coul}) have been calculated, which provide a photoabsorption (σ_{photo}) and a radiative capture cross section (σ_{cap}). Additionally, important information about the nuclear structure of the ^{17}Ne nucleus will be obtained. The analysis is in progress.

1. Introduction

Proton capture reactions play an important role in a nucleosynthesis process, especially in explosive nucleosynthesis such as X-ray bursts [1]. The X-ray binary system (Red Giant - Neutron Star) is characterized by a repeated sudden increase of X-ray emission, which is a consequence of a thermonuclear explosion in the atmosphere of an accreting neutron star. At high temperature and density conditions, the freshly accreted hydrogen and helium ignite. But the slow CNO cycles can be broken out, and the rapid proton capture (rp) process, which is a sequence of proton captures and β^+ decays and which is responsible for the production of proton-rich isotopes up to the mass 100 region, is initiated. The trigger conditions for the burst depend on the efficiency of the breakout reactions from the hot CNO cycle [2].

The possible breakout reactions are still under discussion. At the beginning, only α capture reactions on the waiting-point nuclei of the CNO cycles (^{15}O$(\alpha,\gamma)^{19}$Ne and ^{18}Ne$(\alpha,p)^{21}$Na) have been taken into account [2, 3, 4]. However, at present, the alternative two-proton capture reactions (^{15}O$(2p,\gamma)^{17}$Ne and ^{18}Ne$(2p,\gamma)^{20}$Mg) are also considered [5, 6]. In theoretical predictions, the direct three-particle capture process enhances the reaction rate by a few orders of magnitude [6] compared with a sequential one [5]. In order to verify these calculations, the two-proton radiative capture cross sections of mentioned reactions should be determined. In the present experiment, the ^{15}O$(2p,\gamma)^{17}$Ne reaction has been investigated.

A two-neutron halo structure was already observed for the Borromean nuclei ^{6}He and ^{11}Li [7, 8]. However, an observation of a two-proton halo structure is still a challenge. The Borromean proton dripline nucleus ^{17}Ne is a promising candidate for a two-proton halo, due to a small $2p$ separation energy ($S_{2p} = 960$ keV) [9]. The mixture of the d^2 and s^2 configurations of the two protons outside the ^{15}O core in the ^{17}Ne ground state is still unknown, and the results of theoretical calculations are controversial. In some papers, the s^2 configuration has been predicted to dominate, while in another, the dominating d^2 component has been expected. It seems that the theoretical conclusion about the properties of ^{17}Ne nucleus is still missing [10]. The solution to this situation is an experimental determination of the ^{17}Ne structure.

2. Experimental technique and setup

The experiment has been performed by means of the Coulomb dissociation method, which is typically used to investigate the nuclear structure of exotic nuclei. It is also an important instrument to study relevant reactions for nuclear astrophysics scenarios using an inverse process [11]. In case of several particles in the entrance channel, the time-reversed process is the only way to measure such a complicated reaction. In this method, the Coulomb field of a heavy nucleus is used as a source of virtual photons. Using the virtual-photon theory, the photoabsorption cross section σ_{photo} can be obtained from the differential Coulomb dissociation cross section σ_{Coul}. It can then be converted into the radiative capture cross section σ_{cap} by using the detailed-balance theorem [12]:

$$\sigma_{cap} = \frac{(2j_a+1)\,2}{(2j_b+1)\,(2j_c+1)}\frac{k_\gamma^2}{k^2}\sigma_{photo}. \qquad (1)$$

The LAND-R^{3}B detection setup at GSI was conceived to accommodate such experiments. In the present experiment, the beam was produced by nuclear fragmentation of a ^{20}Ne primary beam on a beryllium production 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 selected secondary beam of ^{17}Ne, with an energy $E = 500$ AMeV, was transported to the experimental setup (Fig. 1) and identified on an event-by-event basis by means of energy-loss, position, and time-of-flight measurements (Fig. 2a).

After the interaction with secondary targets, position measurements, defining the trajectories of the reaction products, energy loss, and time-of-flight measurements were used to identify

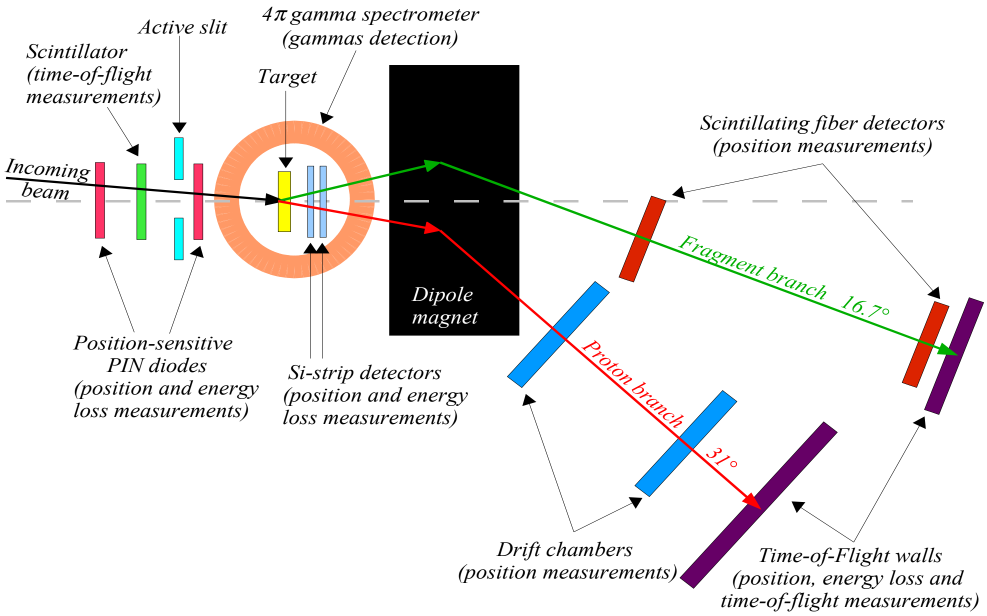

Figure 1. LAND-R^{3}B experimental setup.

outgoing particles (Fig. 2b and 2c), and a 4π gamma spectrometer detected γ-rays emitted by the deexciting fragment.

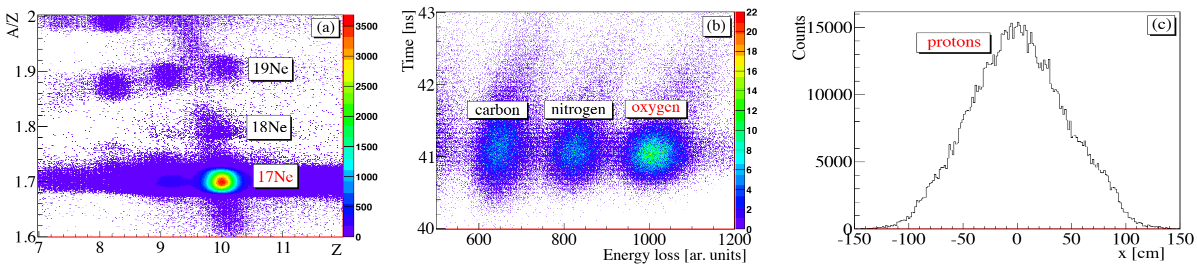

Figure 2. (a) - The identification of incoming beam nuclei; (b) - the identification of outgoing fragments; (c) - detected protons in the Time-of-Flight wall.

To later reconstruct the excitation energy of the desired isotope using the invariant-mass method, the reaction products were tracked on an event-by-event basis. This was done via the magnetic rigidity, time-of-flight, and the known Z (from energy loss) in the outgoing channel:

$$B\rho \propto \frac{A}{Z}\beta\gamma. \tag{2}$$

The measurements were performed using two different targets: a Pb target (200 mg/cm^2) and a C target (370 mg/cm^2). The Pb target was used to investigate the Coulomb dissociation reaction, and the C target to estimate the nuclear contribution. To evaluate the background, the measurements were performed also without any target.

3. Efficiency, acceptance, and γ-rays

The two-proton efficiency of the proton-arm detectors (drift chambers) was estimated to be $55.9 \pm 1.5\%$. Using a simulation within the *R3BRoot* framework, the geometrical acceptance curve of the experimental setup was determined as a function of the relative energy (Fig. 3a).

The γ-rays emitted by the deexciting fragments (^{15}O) were detected in the 4π gamma spectrometer placed around the target. Two groups of excited states of ^{15}O were observed: above 5 MeV and 6 MeV (Fig. 3b). However, only 5% of the events show these excited states, which makes them negligible from the viewpoint of the relative energy spectrum.

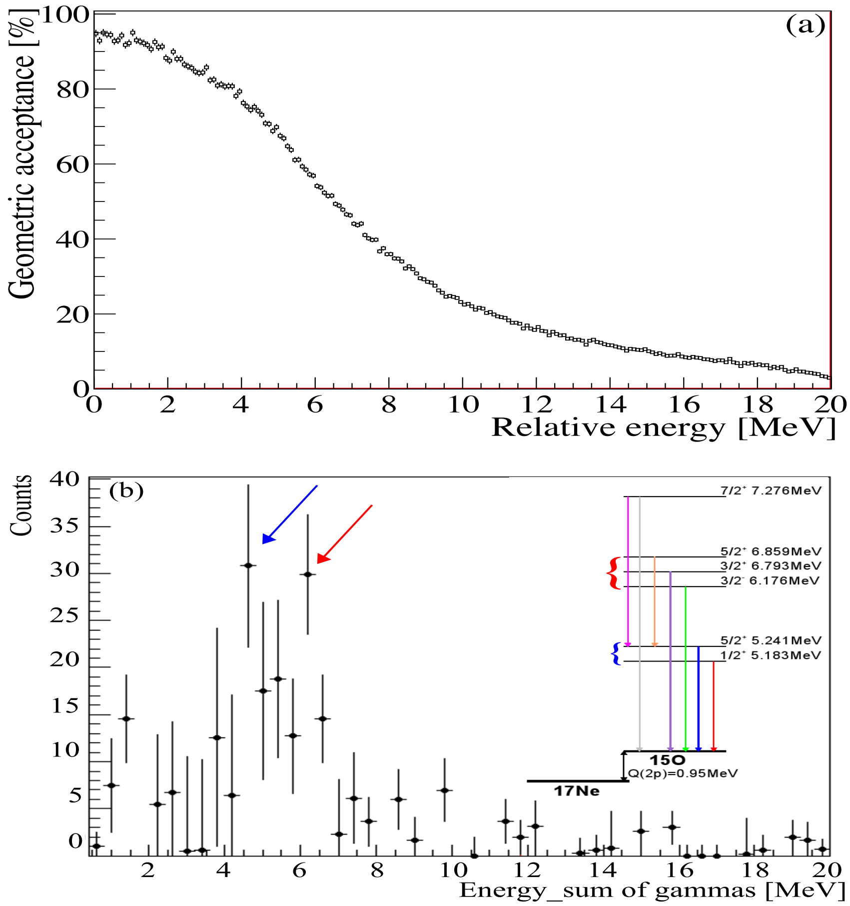

Figure 3. (a) - The geometric acceptance curve; (b) - γ energy sum spectrum.

4. Preliminary results

To calculate a Coulomb dissociation cross section, the following formula was used:

$$\sigma_{Coul} = p_{Pb}\left(\frac{M_{Pb}}{d_{Pb}N_{Av}}\right) - p_C\left(\alpha\frac{M_C}{d_C N_{Av}}\right) - p_{empty}\left(\frac{M_{Pb}}{d_{Pb}N_{Av}} - \alpha\frac{M_C}{d_C N_{Av}}\right), \tag{3}$$

where p is the interaction probability in the target, M is the molar mass of the target material [g/mol], d is the target thickness [g/cm^2], N_{Av} is Avogadro's number [mol^{-1}] and α is a radial scaling factor between Pb and C targets, the value oh which ($\alpha = 1.845$) was estimated from the experimental data. With this formula, the preliminary differential and integral Coulomb dissociation cross section was determined.

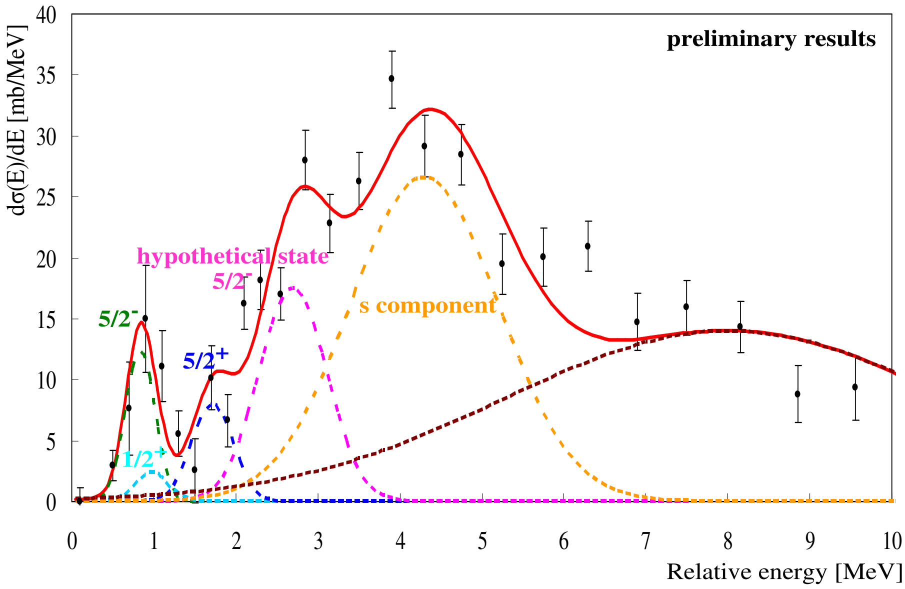

Figure 4. The preliminary fitting of the differential Coulomb dissociation cross section, with existing experimental and theoretical predictions of ^{17}Ne excited states.

For checking the efficiency and the acceptance adjustments, the integral cross section was calculated in two ways, the first using only the ^{15}O data ($\sigma_{Coul_1} = 289{\pm}32(stat.){\pm}35(syst.)$ mb), and the second using the differential cross section spectrum ($\sigma_{Coul_2} = 256 \pm 15(stat.) \pm 18(syst.)$ mb). The reasonable difference ($\Delta = 11\%$) between these two values shows the propriety of these corrections. The shape of the differential cross-section distribution is in agreement with experimental results from Ref. [13] and with the theoretical predictions from Ref. [14]. In the spectrum, the predicted and measured excited states of ^{17}Ne can be distinguished (Fig. 4). The next steps of the analysis will be to calculate the photoabsorption and the radiative capture cross sections.

The $\frac{1}{2}^- \rightarrow \frac{5}{2}^-$ excitation in ^{17}Ne can proceed only via $E2$ photons. Using the virtual photon spectrum (Fig. 5) the $B(E2,^{17}Ne, \frac{1}{2}^- \rightarrow \frac{5}{2}^-)$ value can be derived to compare with the experimental result from Ref. [13]. The result of present work is $B(E2) = 57.6{\pm}10.6\ e^2\text{fm}^4$ (only statistical uncertainty has been included), while the result from Ref. [13] is $B(E2) = 124 \pm 18$ $e^2\text{fm}^4$. The source of this discrepancy is not know yet. The analysis is in progress.

The important information about the three-body system $(core + p + p)$ can provide $2p$ decays. By analyzing different types of energy and angular correlations between internal clusters ($[core, p+p]$ or $[core+p, p]$) in Jacobi coordinates, the mixture of the d^2 and s^2 configurations can be obtained [15]. This method is also used to analyze the ^{17}Ne case. The experimental data are compared with theoretical predictions provided by Ref. [16] using a simulation in the *R3BRoot* framework. The final conclusion is not obtained yet.

5. Summary

By using a ^{17}Ne secondary beam of an energy $E = 500$ AMeV produced in a fragmentation reaction, the $^{15}\text{O}(2p,\gamma)^{17}\text{Ne}$ reaction has been investigated. The incoming beam and outgoing

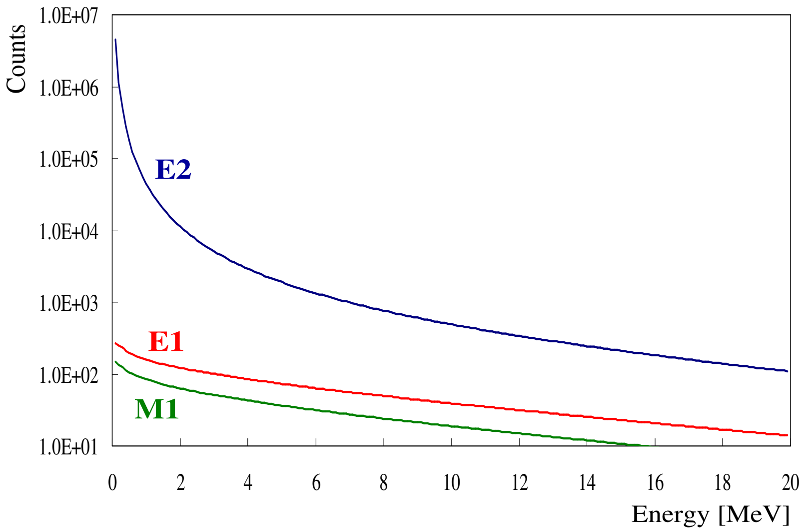

Figure 5. Virtual-photon spectrum for ^{17}Ne @ 500 AMeV on a Pb target.

reaction products have been identified and tracked. The required efficiency and acceptance corrections, as well as the influence of γ-rays emitted by the deexciting fragments have been estimated. The preliminary Coulomb dissociation cross section has been obtained. The photoabsorption and the radiative capture $^{15}\mathrm{O}(2p,\gamma)^{17}\mathrm{Ne}$ cross section calculations, as well as the mixture of the d^2 and s^2 configurations of ^{17}Ne structure analysis are ongoing.

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References

[1] Lahir Ch and Gangopadhyay G 2012 *Int. J. Mod. Phys. E* **21** 1250074
[2] Wiescher M, Görres J, Uberseder E, Imbriani G, and Pignatari M 2010 *Annu. Rev. Nucl. Part. Sci.* **60** 381
[3] Van Wormer L *et al.* 1994 *Astrophys. J.* **432** 326
[4] Wallace R K, Woosley S E 1981 *Astrophys. J. Suppl.* **45** 389
[5] Görres J, Wiescher M, Thielemann F K 1995 *Phys. Rev. C* **51** 392
[6] Grigorenko L V, Zhukov M V 2005 *Phys. Rev. C* **72** 015803
[7] Tanihata I *et al.* 1985 *Phys. Lett. B* **160** 380
[8] Tanihata I *et al.* 1985 *Phys. Rev. Lett.* **55** 2676
[9] Kanungo R *et al.* 2005 *Eur. Phys. J. A* **25** 327
[10] Grigorenko L V, Parfenova Yu L, Zhukov M V 2005 *Phys. Rev. C* **71** 051604
[11] Aumann T 2005 *Eur. Phys. J. A* **26** 441
[12] Baur G and Bertulani C A 1986 *Nucl. Phys.* **A458** 188
[13] Chromik M J *et al.* 2002 *Phys. Rev. C* **66** 024313
[14] Grigorenko L V *et al.* 2006 *Phys. Lett. B* **641** 254
[15] Grigorenko L V *et al.* 2009 *Phys. Lett. B* **677** 30
[16] Grigorenko L V, Parfenova Yu L, Egorova I, *private comunication.*