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# Study of the $^{20,22}$Ne+$^{20,22}$Ne and $^{10,12,13,14,15}$C+$^{12}$C fusion reactions with MUSIC

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**Abstract**

A highly efficient MUlti-Sampling Ionization Chamber (MUSIC) detector has been developed for measurements of fusion reactions. A study of fusion cross sections in the $^{10,12,13,14,15}$C+$^{12}$C and $^{20,22}$Ne+$^{20,22}$Ne systems has been performed at ATLAS. Experimental results and comparison with theoretical predictions are presented. Furthermore, results of direct measurements of the $^{17}$O$(\alpha,n)^{20}$Ne, $^{23}$Ne$(\alpha,p)^{26}$Mg and $^{23}$Ne$(\alpha,n)^{26}$Al reactions will be discussed.

## 1 Introduction

Fusion cross sections play an important role for both nuclear structure and nuclear astrophysics. In nuclear astrophysics the prime example is the $^{12}$C+$^{12}$C fusion reaction, which is the primary route for the production of heavier elements. This is a key reaction in Type Ia supernovae and X-ray bursts and has been the subject of intense experimental efforts. Also, fusion reactions between light neutron-rich nuclei have been proposed to be a possible energy source in X-ray superbursts that originate in the crust of an accreting neutron star [1–3]. The reactions included in the calculations of superburst range from $^{12}$C+$^{12}$C to neutron-rich reactions such as $^{24}$C+$^{24}$C and $^{28}$Ne+$^{28}$Ne. Many of these reactions are outside of our experimental capabilities. However, performing experimental studies in accessible systems will be instrumental to test the predictive power of theoretical models.

For nuclear structure studies, it is important to understand the reaction mechanism of fusion reactions, which according to studies of heavy-ion induced reactions is more complicated than previously suggested. Moreover, there are reported oscillations at energies above the Coulomb barrier in the fusion cross sections of light symmetric systems such as $^{12}$C+$^{12}$C, $^{12}$C+$^{16}$O and $^{16}$O+$^{16}$O (see Refs. [4, 5] and references therein). This phenomenon has been suggested to be cause by the successive penetration of centrifugal barriers with different angular momenta [4]. However, the exact origin is not completely understood and more experimental data are needed in order to gain a better understanding.

The development of the MUlti-Sampling Ionization Chamber (MUSIC) detector [6] opened new possibilities for fusion reaction studies. The high efficiency and flexibility to measure the excitation function in a large energy range in a single measurement make the MUSIC detector an ideal tool for performing measurements of fusion cross sections. Moreover, MUSIC is a self normalizing detector and no additional monitor detectors are needed for the absolute normalization of the beam. This work shows a systematic study of the excitation function of the $^{10,12,13,14,15}$C+$^{12}$C and $^{20,22}$Ne+$^{20,22}$Ne systems and first data of $(\alpha, p)$ and $(\alpha, n)$ reactions with MUSIC.

## 2 The $^{10,12,13,14,15}$C+$^{12}$C experiments

In a series of recent experiment using MUSIC, measurements of fusion reactions between $^{12}$C and $^{10,12,13,14,15}$C were obtained for the first time [7]. The energy of the excitation functions in the center-of-mass (c.m.) ranged from 8-18 MeV. The $^{12,13}$C+$^{12}$C fusion cross sections which were previously measured in Refs. [8,9] were measured in order to verify the technique. The beams from the ATLAS accelerator were delivered to the MUSIC detector which was filled with 200 mbar of $CH_4$ gas. Fig. 1 (left) shows that the detector was able to separate events from the $^{15}$C beam and for evaporation residues produced by $^{15}$C particles in e.g. strip 4 and by the contaminant $^{15}$N beam in e.g. strip 10 due to the difference in the $\Delta$E signals.

The extracted S factors of the $^{10,12,13,14,15}$C+$^{12}$C reactions are shown by

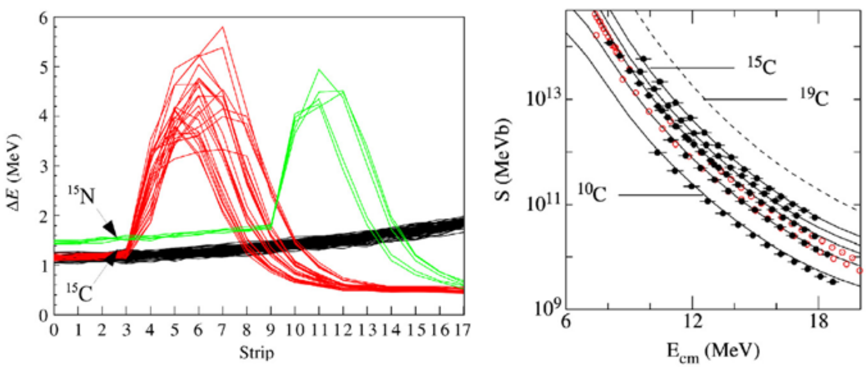


Figure 1: Left: Events measured in MUSIC for the $^{15}$C beam, and for evaporation residues produced by $^{15}$C particles in strip 4 and by $^{15}$N particles in strip 10. Right: S factors of the $^{10,12,13,14,15}$C+$^{12}$C systems measured with MUSIC [7] (solid circles) and the $^{12,13}$C+$^{12}$C systems measured in Refs. [8, 9] (open circles) compared with calculations using the Sao Paulo potential from Ref. [2].

the solid circles in Fig. 1 (right). The solid lines are calculations performed from Ref. [2] using the Sao Paulo potential and the open circles are data for the $^{12,13}$C+$^{12}$C reactions previously obtained in Refs. [8, 9]. As can be seen in this figure there is a very good agreement with earlier measurements between the MUSIC data and with the theoretical predictions.

# 3 The $^{20,22}$Ne+$^{20,22}$Ne experiments

It has been suggested that fusion reactions between neutron-rich nuclei other than carbon, such as oxygen or neon also play a role in the crust of neutron stars. Moreover, it is also of interest to investigate oscillations in Ne+Ne systems, since oscillations have been seen before in light symmetric spin-0 systems, such as carbon and oxygen, and thus, oscillations are also expected to be found in Ne+Ne systems. Therefore, we have started a series of measurement involving Ne isotopes at ATLAS using the MUSIC detector.

These experiments were carried out with $^{20,22}$Ne beams of 120 MeV from the ATLAS accelerator and enriched $^{20}$Ne and $^{22}$Ne gases in MUSIC. As a test the $^{12}$C+$^{20}$Ne excitation function which had been previously measured in Refs. [10] was also studied. Preliminary results of the fusion cross sections of $^{12}$C+$^{20}$Ne measured with MUSIC are shown by squares in Fig. 2 (left) compared with the cross sections previously measured in Ref. [10] (open circles). As seen in the figure there is a good agreement between the two data sets. The cross sections presented in Fig. 2 (right) shows hints of oscillations

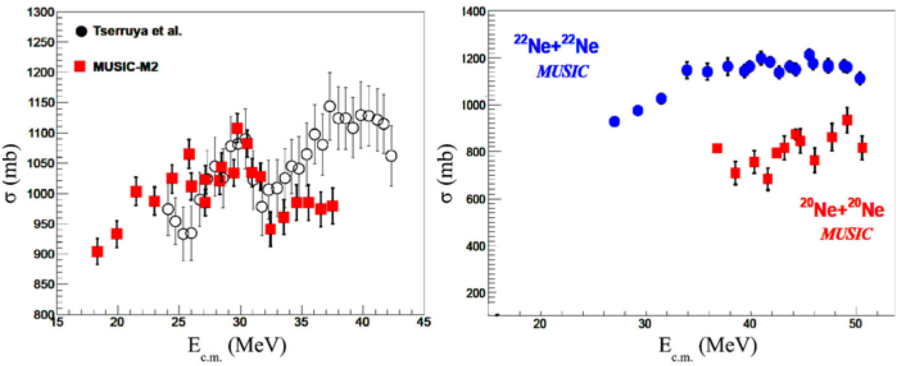


Figure 2: Left: Fusion cross section of $^{12}$C+$^{20}$Ne from Ref. [10] (open circles) and the MUSIC detector (squares). Right: Fusion cross sections of the $^{22}$Ne+$^{22}$Ne (circles) and $^{20}$Ne+$^{20}$Ne (squares) systems measured with MUSIC.

for both the $^{20}$Ne+$^{20}$Ne (squares) and $^{22}$Ne+$^{22}$Ne (circles) systems, but further measurements are needed in order to confirm this claim.

# 4 $(\alpha, n)$ and $(\alpha, p)$ measurements

$(\alpha, p)$ and $(\alpha, n)$ reactions are known to play an important role in nuclear astrophysics. The capabilities of MUSIC for measuring $(\alpha, n)$ reactions were demonstrated using the $^{17}$O$(\alpha, n)^{20}$Ne reaction as a benchmark. Fig. 3 (left) shows that it is possible to separate events of the $(\alpha, n)$ reaction from the incoming beam. The cross sections obtained from this measurement are in good agreement with the cross section from Ref. [11]. This is shown in Fig. 3 (right), where the cross sections of the $^{17}$O$(\alpha, n)^{20}$Ne reaction as a function of c.m. energy extracted from the MUSIC data are compared with the cross sections obtained from Ref. [11]. To compare both data sets the data from Ref. [11] were averaged over a wider energy steps (solid curve in Fig. 3), since it was measured in smaller energy steps.

Recently, we have been successful in measuring the $^{23}$Na$(\alpha, p)^{26}$Mg and $^{23}$Na$(\alpha, n)^{26}$Al reactions using this technique. The $(\alpha, p)$ reaction has been identified in a sensitivity study in Ref. [12] as a key process for the understanding of $^{26}$Al nucleosynthesis in massive stars. Figure 4 (left) shows that MUSIC allows the separation of the traces from $(\alpha, p)$ and $(\alpha, n)$ reactions. The cross sections shown in Fig. 4 (right) for the $^{23}$Na$(\alpha, p)^{26}$Mg and $^{23}$Na$(\alpha, n)^{26}$Al reactions were measured simultaneously with two different beam energies 57.5 MeV and 52 MeV labeled as High and Low energy, re-

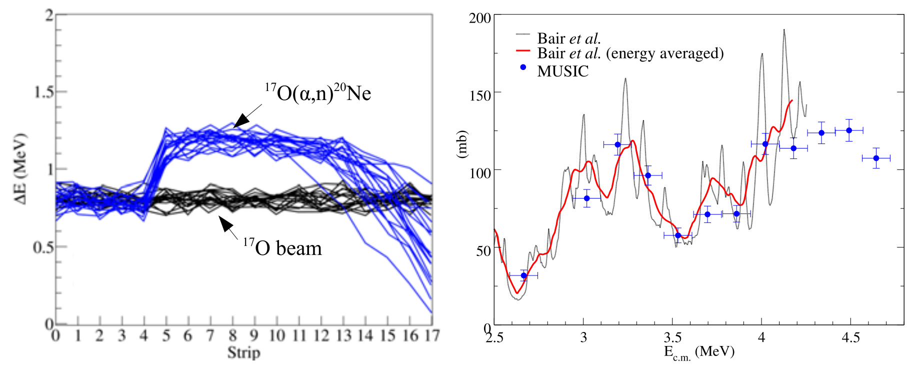


Figure 3: Left: Events of the $^{17}\mathrm{O}(\alpha, n)^{20}\mathrm{Ne}$ reaction occurring in strip 5 and of the $^{17}\mathrm{O}$ beam. Right: Cross section of the $^{17}\mathrm{O}(\alpha, n)^{20}\mathrm{Ne}$ reaction, obtained from Ref. [11] (dashed line) and its energy-averaged cross section (solid line) compared with the MUSIC data (solid circles).

spectively. This preliminary analysis shows that our data are in good agreement with the statistical model calculations performed in Ref. [13] (dashed lines). These are important results because MUSIC can now be used to study $(\alpha, p)$ and $(\alpha, n)$ reactions directly, offering a unique opportunity of study for $\alpha$-capture reactions with both stable and radioactive beams.

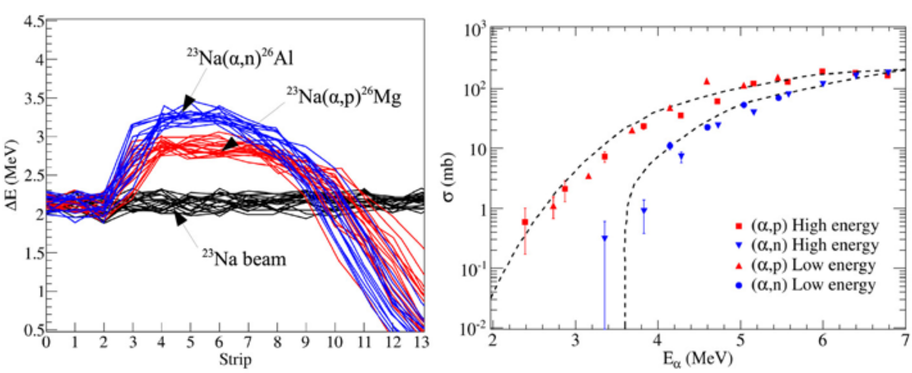


Figure 4: Left: Events for reactions occurring in strip 3 for $(\alpha, p)$, $(\alpha, n)$ and the $^{23}\mathrm{Na}$ beam in the MUSIC detector. Right: Cross section of the $^{23}\mathrm{Ne}(\alpha, p)^{26}\mathrm{Mg}$ and $^{23}\mathrm{Na}(\alpha, n)^{26}\mathrm{Al}$ reactions.

# 5 Summary

A highly efficient active target detector system has been developed. The fusion cross sections of $^{10,12,13,14,15}$C+$^{12}$C were measured and compared with theoretical predictions. For experiments with radioactive $^{10,14,15}$C beams a good agreement between our results and theoretical calculations was found. Measurements of the $^{12,13}$C+$^{12}$C systems are in good agreement with the cross sections measured by standard techniques in Refs. [8, 9]. Preliminary results of the fusion cross sections of $^{20,22}$Ne+$^{20,22}$Ne are also presented. Along with that, MUSIC has been successfully used to measure the $^{17}$O$(\alpha, n)^{20}$Ne, $^{23}$Na$(\alpha, p)^{26}$Mg and $^{23}$Na$(\alpha, n)^{26}$Al reactions, opening new possibilities for the study of $\alpha$-induced reactions.

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