STRUCTURE OF ^{24}Mg EXCITED STATES AND THEIR INFLUENCE ON NUCLEOSYNTHESIS* **

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(Received December 14, 2016)

The main idea of the two presented experiments is to study the decay of resonances in ^{24}Mg at excitation energies above the ^{12}C+^{12}C decay threshold, in the astrophysical energy region of interest. The measurement of the ^{12}C(^{16}O,α)^{24}Mg* reaction was performed at INFN-LNS in Catania. Only the α+^{20}Ne decay channel of ^{24}Mg is presented here, because it was a motivation for conducting a new experiment, a study of the ^{4}He(^{20}Ne,^{4}He)^{20}Ne reaction, performed at INFN-LNL in Legnaro. Some preliminary results of this measurement are also presented.

DOI:10.5506/APhysPolB.48.319

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 28–September 4, 2016.

** This work has been supported in part by the Croatian Science Foundation under the project "Experimental nuclear physics inputs for thermonuclear runaway" funded within the EUROCORES EuroGENESIS program, and under the project IP-11-2013-7194. The author would like to thank the staff of INFN-LNS and INFN-LNL for their support and assistance.

1. Introduction

Experimental studies in 1960 showed that the excitation functions for the elastic [1] and the reaction channels [2] in the ^{12}C+^{12}C system have unique and prominent resonant structures. Further studies [3] showed that both carbon nuclei retained their identities in these resonant states which led to the idea of quasimolecular states. These discoveries triggered a lot of experimental and theoretical work which aimed to understand the underlying phenomena, but some of the questions still remain unanswered. The subject is still interesting today not just because of the cluster structure of these resonances but also because of the important role that they play in carbon-rich stellar systems, such as super AGB stars, supernovae Type Ia and superbursts [4]. The relevant energy ranges of the cross-section measurements for super AGB and SN Type Ia stars is $E_{\rm cm} = 1.5$–3.3 MeV for the ^{12}C+^{12}C reaction. Current measurements extend down to 2.10 MeV [5]. This region of astrophysical interest is far below the Coulomb barrier ($V = 5.8 \pm 0.3$ MeV [6]), which makes measurements quite difficult. Due to the resonant structures at higher energies, extrapolations of the cross section to the lower energy region is unreliable. So, instead of the direct cross-section measurements used in [1, 2, 5], indirect measurement methods were used in these two experiments; the resonant particle spectroscopy method in the Catania experiment and the resonant elastic scattering method in the Legnaro experiment.

2. Catania experiment

The ^{12}C(^{16}O,α)^{24}Mg* reaction was measured at INFN-LNS, in Catania, using Tandem accelerator beam, at $E(^{16}\text{O}) = 94$ MeV. Measured decay channels of ^{24}Mg* and the matching threshold energies are presented in Table I. Our experimental setup consisted of 6 Si detector telescopes (Fig. 1), each with one thin detector of 19 or 20 μm, and one thick Position Sensitive Silicon Strip Detector (PSSSD) or a Double Sided Silicon Strip Detector (DSSSD).

TABLE I

Decay channels of ^{24}Mg* and the threshold energies $E_{\rm th}$ at the excitation energy of ^{24}Mg.

Decay channel	α+^{20}Ne	p+^{23}Na	^{12}C+^{12}C	^{8}Be+^{16}O
$E_{\rm th}$ [MeV]	9.31	11.69	13.93	14.14

All observed channels were analysed, except the p+^{23}Na channel, which was discarded during the experiment because it was not possible to distinguish the proton signal from the noise. The most prominent resonances in

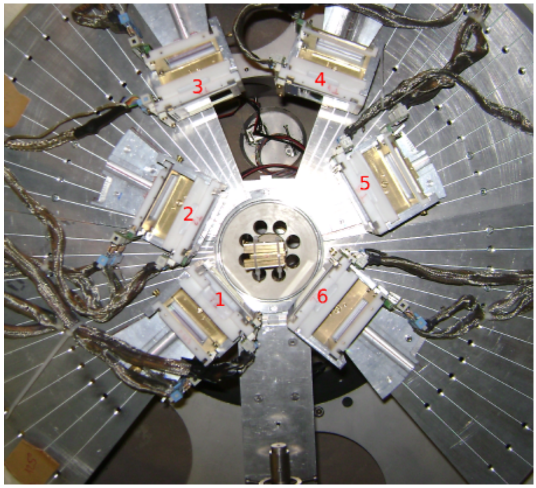

Fig. 1. Experimental setup of Catania experiment.

^{24}Mg, in this astrophysical energy region of interest, were observed in the $\alpha+^{20}$Ne channel. In Fig. 2, the spectrum of the ^{24}Mg excitation energy, for one of the measured combinations of telescopes is presented (telescopes T4-T2) in Fig. 1, including the determined spin of a few of the observed states. To determine the spin of these states, the angular correlation method was used [7]. The rising/grey line represents the calculated geometrical de-

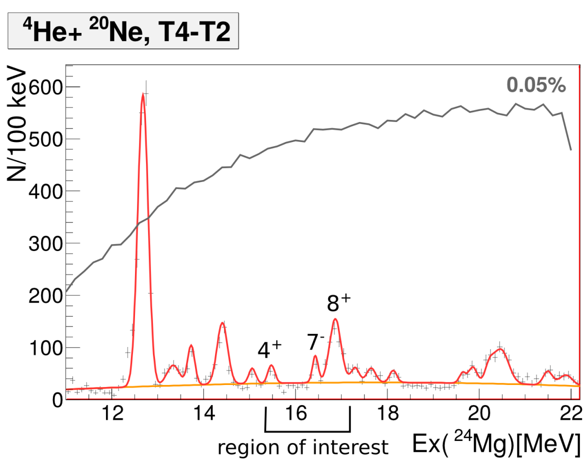

Fig. 2. (Colour on-line) Spectra of ^{24}Mg excitation energies obtained from the ^{12}C(^{16}O, $\alpha\alpha$)^{20}Ne data at $E_{\rm beam} = 94$ MeV, with determined spin of states, measured at INFN-LNS. The rising (grey) line represents the calculated geometrical detection efficiency with the value presented on the right-hand axis, eff.

tection efficiency. Only higher spin states were observed in this measurement, that cannot play a role in the carbon burning process. Since the Catania measurement was planned in a way to detect all of the decay channels (Table I), a new experiment was devised to only measure the $\alpha+^{20}$Ne channel.

3. Legnaro experiment

This new experiment measured the ^{4}He(^{20}Ne,^{4}He)^{20}Ne scattering reaction at INFN-LNL in Legnaro, and used ALPI-PIAVE accelerator facility beam, at $E_{\mathrm{beam}} = 60$, 52 and 44 MeV. A schematic drawing of the reaction chamber is shown in Fig. 3. The reaction chamber was filled with the helium gas, with the pressure set in order to stop the ^{20}Ne beam entering the Si detector telescope at 0°. Only the analysis of the data collected by the telescope at 0° is presented here.

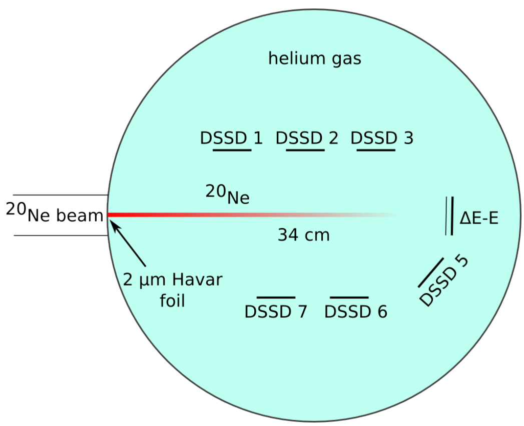

Fig. 3. Schematic drawing of the reaction chamber for Legnaro experiment.

Spectra of the ^{24}Mg excitation energies, obtained from the measurements at the three different beam energies are presented in Fig. 4. Spectra are normalized and corrected for the detection efficiency. From the spectra in Fig. 4, it is clear that there is a difference in the differential cross section for the spectra obtained at different beam energy measurements, *i.e.* there is a strong contribution of inelastic scattering. A difficulty with using this method is that one cannot resolve $\alpha+^{20}$Ne from the $\alpha+^{20}$Ne* or $\alpha+^{20}$Ne** channels. Since the highest energy events must originate from the collisions with the largest center-of-mass energy $E_{\mathrm{cm}} = E_{\mathrm{max}}$, and if the decay product ^{20}Ne is, for example, in its first excited state at 1.634 MeV, then the E_{cm} will be reduced for this excitation energy of the ^{20}Ne, so $E_{\mathrm{cm}} = E_{\mathrm{max}} - 1.634$ MeV and part of the spectrum, where the $E_{\mathrm{cm}} > E_{\mathrm{max}} - 1.634$ MeV will be free of this inelastic contribution. These particular beam energies were chosen, so that when the region free of the inelastic contribution at higher beam energy stops, this region for the lower beam energy starts. In that way, one is certain of the amount of the inelastic contribution.

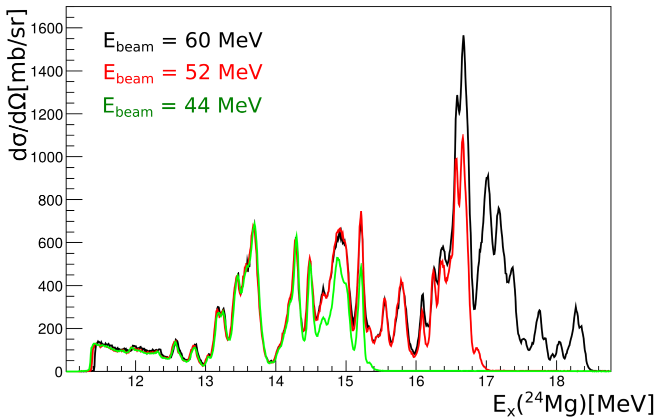

Fig. 4. Excitation spectra for ^{24}Mg, normalized and corrected for the detection efficiency, for three different beam energies, obtained from the ^{4}He(^{20}Ne,^{4}He)^{20}Ne data measured at INFN-LNL.

The R-matrix method for the cross-section analysis was used to obtain information about the position, spin and decay widths of the states observed in the spectra in Fig. 4. The R-matrix fit was performed using the code AZURE2 [8] and as the input parameters, the results from the direct measurements ^{20}Ne(α,α_0)^{20}Ne [9] were used. In Abegg's and Davis' measure-

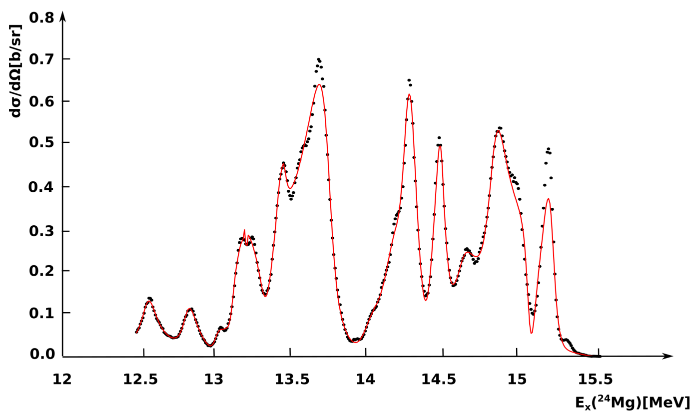

Fig. 5. (Colour on-line) Black dots are the measured Legnaro experimental ^{4}He(^{20}Ne,^{4}He)^{20}Ne data obtained for $E_{\rm beam} = 44$ MeV, while the black (red) line is result of the R-matrix fit, $\chi^2/N \approx 60$.

ment, the beam energy was varied in steps at 10–15 keV and their data show high complexity, with around ≈ 120 states in the $E_x(^{24}\mathrm{Mg}) = 12.5$ MeV–18.5 MeV region, but they also state that "the level widths carry little significance since they probably reflect biases in data taking and analysis ..." [9], so one has to be quite careful in using these parameters. During the fit, partial widths for the $p+^{23}\mathrm{Na}$ and the $\alpha+^{20}\mathrm{Ne}^*$ channel were added if that improved the fit. The R-matrix fit to the spectra obtained with the $E_{\mathrm{beam}} = 44$ MeV showed 27 states and quality of the fit is represented with $\chi^2/N \approx 60$ (Fig. 5).

4. Summary

The spectrum obtained for $E_{\mathrm{beam}} = 44$ MeV, in Fig. 5, does not cover the main energy region of astrophysical interest, so the R-matrix fit for the spectra obtained for the two higher beam energies is needed in order to determine if there is an excited state in this region that could contribute to the carbon burning process. In Abegg's and Davis' paper [9], there is a 0^+ state at 15.68 MeV, but this state is quite weak and other states in this astrophysical energy region of interest are higher spin states. An R-matrix fit for the spectra measured for the two higher beam energies is in progress, but preliminary results show that it does not seem likely that there is the 0^+ state in this astrophysical energy region of interest.

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