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# Study of Nuclear Structure of $^{13}\text{C}$ and $^{20}\text{Ne}$ by Low Energy Nuclear Reactions

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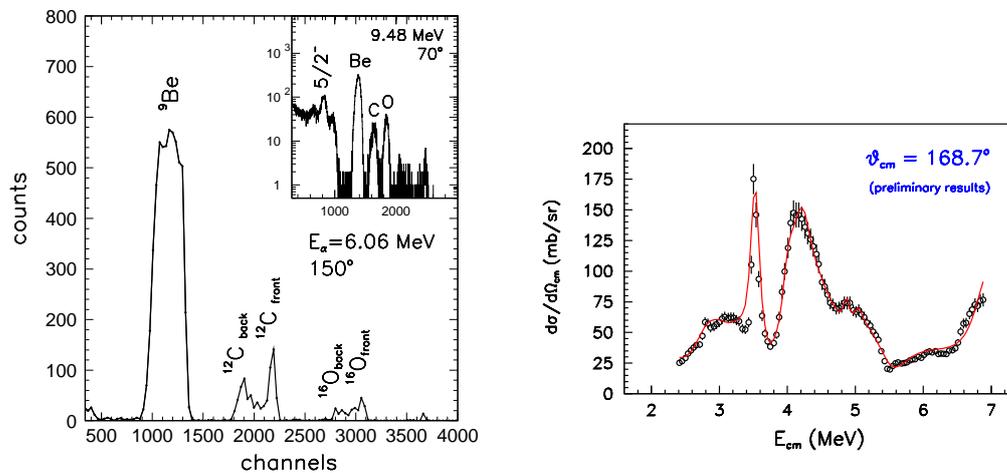
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**Abstract.** We report some recent experimental results on the spectroscopy of  $^{13}\text{C}$  and  $^{20}\text{Ne}$  nuclei by means of low energy nuclear reactions carried out with high resolution electrostatic accelerators. In the case of  $^{13}\text{C}$  we investigated the possible existence of  $\alpha$ -cluster states above the  $\alpha$  emission threshold by means of low energy elastic resonant scattering  $\alpha+^9\text{Be}$  in direct kinematics. Excitation functions show the presence of various resonances that have been reproduced by  $R$ -matrix fit. We studied also the structure of  $^{20}\text{Ne}$  by means of the  $^{19}\text{F}(p,\alpha_0)$  reaction at sub-barrier energies. The spectroscopy of  $^{20}\text{Ne}$  excited states in the region  $E_x \approx 13.5\text{-}14.0$  MeV can be probed by analyzing experimental angular distributions and excitation functions. This reaction plays an important role also in the CNOF cycle and is an important ingredient to describe hydrogen-induced destruction of fluorine in massive stars. For this reason we investigated the trend of  $S$ -factor, that has been compared with results previously reported in the literature.

## 1. Introduction

Low Energy Nuclear Reactions between light ions are an important tool for carefully probing the structure of light nuclei [1]. In particular, it is possible to deduce information about the possible existence of  $\alpha$ -cluster states in light nuclei, a subject of large interest in Nuclear Physics [1, 2]. To this aim, different type of nuclear reactions can be used. For example, direct reactions as ( $^6\text{Li},d$ ) and ( $^7\text{Li},t$ ) at some tens of MeV, leading to  $\alpha$ -transfer processes on the target nucleus, have been often used to probe the existence of  $\alpha$ -structures in light nuclei [3, 4]. Other experimental ways to probe the  $\alpha$ -structure of light nuclei are the study of resonant elastic scattering (in direct or inverse kinematic) of  $^4\text{He}$  nuclei on various targets [5, 6, 7] or, in general, the study of nuclear reactions leading to the formation of a given compound nucleus that subsequently de-excites by emitting  $\alpha$ -particles. In the first part of this paper we describe some investigations on the structure of the  $^{13}\text{C}$  nucleus via the resonant elastic scattering of  $\alpha$  particles on  $^9\text{Be}$  in direct kinematics [8, 9]. In this way it is possible to explore an excitation energy region in  $^{13}\text{C}$  where the existence of rotational bands built on molecular states has been suggested [10]. In the second part of the paper we discuss on the spectroscopy of  $^{20}\text{Ne}$  excited states by means





**Figure 1.** (Left panel) Experimental spectra of  $\alpha + {}^9\text{Be}$  scattering at  $150^\circ$  and  $70^\circ$  (insert), at 6.06 and 9.48 MeV bombarding energies. (Right panel) Elastic scattering excitation function obtained at  $\theta_{\text{cm}} = 168.7^\circ$  (open circles) and preliminary  $R$ -matrix fit to the experimental data (red line).

of the  ${}^{19}\text{F}(p, \alpha_0)$  reaction at sub-Coulomb energies [11]. In this case the analysis of excitation functions and angular distributions allows to refine the spectroscopy of  ${}^{20}\text{Ne}$  in the excitation energy range  $E_x \approx 13.5$ -14.0 MeV, where uncertain  $J^\pi$  assignment are still persisting in the literature. Furthermore we extracted the  $S$ -factor in the energy region  $E_{\text{cm}} \simeq 0.57$ -1.0 MeV, where two different trends are reported in the literature. Our work allows to shed light on this discrepancy and points out the need for further measurements at lower energies. Good quality data at low energies are important because this reaction is involved in the CNOF cycle during the hydrogen-burning phase in stars [12] and represents an important channel of fluorine destruction in hydrogen-rich stellar environments [13, 14]. Both the experiments have been carried out at the TTT-3 tandem in Naples [15] and will be briefly described in the following paragraphs.

## 2. Structure of ${}^{13}\text{C}$ via $\alpha + {}^9\text{Be}$ elastic scattering

Between the various non-self-conjugated nuclei, the study of  ${}^{13}\text{C}$  excited states above the  $\alpha$  emission threshold probably constitutes one of the most interesting physical cases. In fact, the structure of some excited states could be described in term of an excitation of the Hoyle state in a  ${}^{12}\text{C}^*$  core coupled with a covalent neutron [16]. Information on the structure (included the radius and the moment of inertia) of these states could be useful to shed light on the structure of the  ${}^{12}\text{C}$  nucleus. In this framework the possible presence of molecular-like states in highly-lying excited states of  ${}^{13}\text{C}$  has been suggested in [10] starting from the available data reported in the literature [17]. This and other theoretical works stimulated experimentalists to refine the spectroscopy of  ${}^{13}\text{C}$  near and above the  $\alpha$  threshold.

A powerful way to perform these investigations is represented by the analysis of resonances in  $\alpha + {}^9\text{Be}$  elastic scattering excitation functions at backward angles. Unfortunately, very few experimental data have been reported in the literature. An old paper by Goss et al [5] reported on the elastic scattering in direct kinematics in a broad angular range ( $50$ - $160^\circ$ ) but in a limited bombarding energy domain ( $E_{\text{lab}} \approx 2.0$ - $5.0$  MeV), while in a more recent paper Freer et al [6] reported an excitation function obtained with the inverse kinematic thick target method

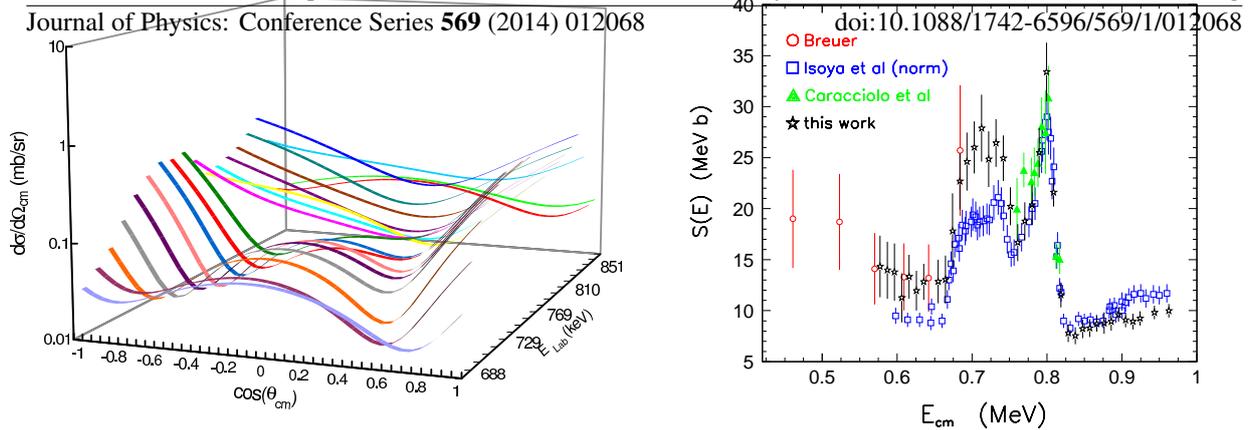
at around  $180^\circ$  in the energy domain  $E_{cm} \approx 2.0\text{-}7.0$  MeV. In both cases, information on the  $J^\pi$  of various states have been deduced by  $R$ -matrix fit of experimental data. Anyway, some uncertainties on  $J^\pi$  assignments are still persisting, thus stimulating a new experiment covering a broader energy and angular domain. We performed this experiment in direct kinematics at the TTT-3 tandem accelerator in Naples [15]; details on this experiment can be found in [8, 9]. We checked the absolute scale of experimental cross sections by performing both thin and thick target experiments [8]. An example of spectra obtained at backward angles is reported in the left panel of Figure 1. The presence of elastically and inelastically scattered  $\alpha$  particles from  $^9\text{Be}$  and contaminants constituting the target is recognized by kinematics and energy loss considerations.

An example of excitation function of the  $\alpha+^9\text{Be}$  elastic scattering at  $\theta_{cm}=168.7^\circ$  is reported in the right panel of Figure 1 (open circles). The red solid line indicates the result of a preliminary  $R$ -matrix fit to the experimental data, obtained by using the *minRmatrix* code [18, 19]. The effect of target thickness has been taken into account in performing the fit procedure. These results are still preliminary and will be extended in the future to other excitation functions obtained at different angles. Nevertheless, we can extract some interesting information from this preliminary analysis. First of all, in the energy domain here explored, it seems that no  $1/2$  states are excited, in agreement with data by [6]. Therefore the excitation energy of a possible state obtained by coupling in  $s$ -wave a neutron with a  $^{12}\text{C}$  core excited to the Hoyle state should be lower than the minimal excitation energy probed in this experiment, and this is in agreement with recent AMD calculations [16]. Another interesting point concerns the resonant structure at  $E_{cm} \approx 3.5$  MeV. Our preliminary results pointed out the presence of two close-lying states with  $J^\pi=5/2^-, 7/2^+$  with quite low values of dimensionless reduced widths for the  $\alpha_0$  channel (of the order of some percent of the Wigner limit). These preliminary results are in good agreement with the findings of [5] and seems to rule out the presence of a  $9/2^-$  state at this excitation energy, needed to support the existence of the molecular negative-parity rotational band in  $^{13}\text{C}$ . Further investigations on the present experimental data are currently going on.

### 3. Investigation of the $^{19}\text{F}(\text{p},\alpha_0)$ reaction at low energies

The investigation of low energy  $^{19}\text{F}(\text{p},\alpha_0)$  and  $^{19}\text{F}(\text{p},\alpha_\pi)$  reactions has been used in the past to probe the structure of  $^{20}\text{Ne}$ , which is a self-conjugated nucleus and can show pronounced  $\alpha$ -cluster structures [20]. To this aim experimental efforts have been performed [21, 22] to evidence the existence of quartet excitations in this nucleus [23, 24]. Unfortunately, ambiguities in the spectroscopy of some excited states are still persisting, especially in the excitation energy region around 13.3-14.0 MeV [25]. Beyond the spectroscopic motivation, the  $^{19}\text{F}(\text{p},\alpha)$  reaction plays a significative role in Nuclear Astrophysics because it closes the CNOF cycle in the hydrogen-burning phase of massive stars [12] and can represent an important channel of fluorine destruction in hydrogen-rich stellar environments [13, 14]. Despite of this interest, very few (and often contrasting) data-sets of the  $S$ -factor at  $E_{cm} < 1$  MeV have been reported in the literature, thus preventing an accurate reaction rate determination at astrophysical energies [26]. Taking into account both these aspects, we performed a new experiment at the TTT-3 tandem accelerator in Naples, aimed at measuring angular distributions and excitation functions of the  $^{19}\text{F}(\text{p},\alpha_0)$  reaction in the bombarding energy domain  $E_p \approx 0.6\text{-}1.0$  MeV. The details of this experiment are widely discussed in [11]. In the following sections we report some experimental findings related to this experiment.

An array of 12 silicon detectors covering a large angular range has been used as detection system. Thin aluminium foils preceded silicon detectors in order to stop the high flux of scattered particles; at variance, they allow the passing through of high energy  $\alpha$ -particles emitted in the  $^{19}\text{F}(\text{p},\alpha_0)$  reaction ( $Q=8.114$  MeV). The obtained experimental spectra are practically background-free. Due to the low bombarding energy domain ( $E_p \approx 0.6\text{-}1$  MeV), only  $s$ ,  $p$  and  $d$  partial waves are expected to mainly contribute; for this reason, angular distributions have been



**Figure 2.** (Left panel) Best fits of  $^{19}\text{F}(p,\alpha_0)$  experimental angular distributions in terms of Legendre polynomials, as a function of the bombarding energy. (Right panel)  $^{19}\text{F}(p,\alpha_0)$   $S$ -factor extracted in the present experiment [11] and compared with literature data [21, 27, 28] as reported in NACRE [26].

fitted with Legendre polynomials up to 4<sup>th</sup> degree [21, 27, 28]. The distributions of coefficients of the polynomial expansions around resonance energies allow to estimate the relative orbital angular momentum in the outgoing channel and therefore the  $J^\pi$  of excited states [21, 27, 28]. The evolution of angular distributions as a function of bombarding energy is displayed in Figure 2 (left panel). A continuous shape evolution is evident, pointing out the excitation of various states with different  $J^\pi$ . The analysis of angular distributions has been largely discussed in Ref. [11]; in this way we obtained  $J^\pi$  assignment of various states for which contrasting values were reported in the literature [25]. For example, the  $E_p=842$  keV ( $E^*=13.642$  MeV) state has been ambiguously reported to be  $0^+$  [21, 29] or alternatively  $2^+$  [28]. From the analysis of the present data in the  $E_p=810$ -860 keV interval we deduce a  $0^+$  assignment for the 842 keV state. Moreover, a contribution from a  $1^-$  state at  $E_p \approx 825$  keV partially merged into the previous one has been seen [11]. Further details on this analysis can be found in Ref. [11].

As discussed at the beginning of this paragraph, the  $^{19}\text{F}(p,\alpha)$  reaction plays an important role also in Nuclear Astrophysics, with the  $^{19}\text{F}(p,\alpha_0)$  channel being dominant at  $T < 0.1$  GK [30]. The recommended values of the  $^{19}\text{F}(p,\alpha_0)$   $S$ -factor at low energies are reported in NACRE [26]. They are taken from Breuer ( $E_{cm}=461$ -684 keV [27]), Isoya et al ( $E_{cm}=598$ -1385 keV [28]), Caracciolo et al ( $E_{cm}=760$ -817 keV [21]) and Cuzzocrea et al ( $E_{cm}=1476$ -2544 keV, [22]). In more recent times, indirect data obtained with the Trojan Horse Method pointed out the role played by the low-energy resonance at  $E_{cm} = 113$  keV [14].

We can recognize two different behaviors of experimental data at  $E_{cm} < 0.7$  MeV, where the data of Refs. [27] and [28] differ by a factor of  $\approx 40\%$ . This discrepancy affects the non-resonant extrapolation made in [26], and therefore the reaction rate determination at stellar energies. In the experiment here discussed, we extracted the  $S$ -factor from the experimental differential cross sections in the range  $E_{cm}=577$ -982 keV [11]. The results are shown in the right panel of Figure 2 together with data reported in NACRE [26]. A reasonable agreement (within the errors) between present results and Refs. [21, 28] is seen in the energy region  $E_{cm} \approx 800$  keV. Furthermore, the  $S$ -factor smoothly increases with decreasing energy at  $E_{cm} < 650$  keV, in good agreement with results by [27]. This behavior could be attributed to the excitation of two broad states ( $0^+, 1^-$ ) at  $E^* = 13.224$  MeV [27]. Moreover, our data and Breuer ones [27] in the  $E_{cm} \approx 550$ -650 keV interval are about 40% larger than the Isoya et al ones [28]; consequently, extrapolations mainly based on this data set can underestimate the low energy non-resonant  $S$ -factor values. These findings stimulate to explore the low energy region of the  $^{19}\text{F}(p,\alpha_0)$   $S$ -factor with new direct investigations. To this aim, a new experiment has been recently performed at Laboratori

Nazionali di Legnaro, exploring the  $^{19}\text{F}(p,\alpha_0)$   $S$ -factor down to  $E_{cm} \approx 180$  keV. Data analysis is currently going on.

#### 4. Conclusions

In this paper we reported some recent results about the structure of  $^{13}\text{C}$  and  $^{20}\text{Ne}$  nuclei, investigated by means of resonant elastic scattering ( $\alpha+^9\text{Be}$ ) and low energy nuclear reactions ( $^{19}\text{F}(p,\alpha_0)$ ) respectively. On the side of  $^{13}\text{C}$  structure, the appearance of anomalies in the differential cross sections is associated to the excitation of various states in  $^{13}\text{C}$  above the  $\alpha$  threshold.  $R$ -matrix analysis of experimental data is currently in progress. Concerning the  $^{19}\text{F}(p,\alpha_0)$  reaction, from the analysis of angular distributions we estimated the  $J^\pi$  of various excited states of the compound nucleus  $^{20}\text{Ne}$ , trying to solve some ambiguities still persisting in the literature. The trend of the  $S$ -factor has been also explored down to  $E_{cm} \approx 0.55$  MeV and has been compared with results reported in the literature, pointing out the need to increase the non-resonant contribution with respect to the currently adopted extrapolations. In this framework a new experiment, aimed at exploring the  $S$ -factor down to  $E_{cm} \approx 0.18$  MeV, has been recently performed and the analysis is currently ongoing.

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