Spectroscopy of Light Nuclei with Low Energy Nuclear Reactions

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Abstract. We discuss new results concerning the investigation of the \(^{19}\text{F}(p,\alpha)\)\(^{16}\text{O}\) and \(^{10}\text{B}(p,\alpha)\)\(^{7}\text{Be}\) reactions at low energies. Both reactions are important for the nuclear spectroscopy of the formed compound nucleus, i.e. \(^{20}\text{Ne}\) and \(^{11}\text{C}\) respectively, and play a role in nuclear astrophysics. For the \(^{10}\text{B}(p,\alpha)\)\(^{7}\text{Be}\) case, a comprehensive analysis of our reaction data and other scattering data points out the possible presence of an unreported state in \(^{11}\text{C}\) at \(E_x \approx 9.36\) MeV. For the \(^{19}\text{F}(p,\alpha)\)\(^{16}\text{O}\) case, the study of the low energy angular distributions testifies the role played by low energy resonances in the S-factor, leading to an enhanced reaction rate at stellar energies.

1. Introduction

Nuclear collisions between light ions represent a very useful tool to explore the structure of light nuclei. In particular, it is possible to deduce information about the appearance of \(\alpha\)-cluster states in light nuclei. Different types of experimental nuclear techniques can be used to investigate these aspects. For example, direct \(\alpha\)-transfer [1, 2, 3] and sequential break-up [4, 5, 6, 7] reactions have been widely used to make the spectroscopy of light nuclei with medium-energy stable and radioactive beams. At low energies, other powerful tools to do nuclear spectroscopy of light nuclei are the study of resonant elastic scattering of \(^{4}\text{He}\) nuclei on various targets, both in direct and inverse kinematics [8, 9, 10, 11] or, in general, the study of nuclear reactions leading to the formation of a compound nucleus that decays by \(\alpha\)-particle emission [12, 13, 14]. Beyond ion collisions, other techniques, such as radioactive decay [15], electron scattering [16], \(\gamma\)-induced reactions [17] have been used advantageously to investigate the cluster structure of light nuclei.

In the first part of these proceedings we will describe some results on the structure of the \(^{11}\text{C}\) nucleus, obtained by analysing the \(^{10}\text{B}(p,\alpha)\)\(^{7}\text{Be}\) reaction at 0.6 - 1.1 MeV bombarding energies. Because of various experimental difficulties due to the reaction kinematics and the presence of contaminants in the target, the data reported in the literature in this energy range are very few, and often affected by large uncertainties [18, 19]. Moreover, the spectroscopy of \(^{11}\text{C}\) is full of ambiguities in the \(E_x = 9.0 - 12\) MeV range, including the energy range discussed here. In our experiment, we measured the integrated reaction cross section and S-factor. They are about 30% lower than previous estimate [20]. An \(R\)-matrix fit [21] of \(^{10}\text{B}(p,\alpha)\)\(^{7}\text{Be}\) and \(^{10}\text{B}(p,\alpha_1)\)\(^{7}\text{Be}\) reactions and \(^{10}\text{B}(p,p\alpha)\)\(^{10}\text{B}\) scattering data allowed to determine resonance parameters for excited states in \(^{11}\text{C}\) in the excitation energy domain \(E_x \approx 9-11\) MeV, and pointed out the possible existence of a state at \(E_x \approx 9.36\) MeV.

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In the second part of these proceedings we will discuss the results obtained by analysing the structure of $^{20}$Ne by means of the $^{19}$F($p,α$) reaction at sub-Coulomb energies. The analysis of excitation functions and angular distributions allow to refine the $^{20}$Ne spectroscopy in the $E_x ≈ 13.0-14.0$ MeV region [22, 23]. We measured the $S$-factor distribution in the $E_{cm} ≈ 0.18-1.1$ MeV range, where very few data have been reported in the literature [24, 25, 26]. The lowermost energy data that we have obtained are close to the stellar energy domain [26]; they are important because this reaction is involved in the CNOF cycle during the hydrogen-burning phase and represents an important channel of fluorine destruction in hydrogen-rich environments of massive stars [27]. Our data point out the presence of low-energy resonances, in agreement with results obtained with indirect experiments based on the Trojan Horse Method [28, 29].

They can increase up to a factor ≈2 the reaction rate at temperatures typical of AGB stars.

2. The $^{10}$B($p,α$)$^7$Be reaction and the structure of $^{11}$C

The $^{10}$B($p,α$)$^7$Be reaction is important in various fields of nuclear physics. In fact, it allows to study the spectroscopy of the non self-conjugated $^{11}$C compound nucleus [30], with particular regard to the appearance of $α$-cluster states (see, e.g. [12, 13]). Furthermore, it is important to accurately describe the destruction of the $^{10}$B isotope in stars [19]. Finally it is involved in radio-protection issues in Nuclear Fusion technology [31].

Unfortunately, direct data reported in the literature at low bombarding energies, especially in the $E ≈ 1 – 2$ MeV region, are quite few [18, 20], being often characterized by large error bars. Considering all these reasons, we decided to perform a new experiment to measure the $^{10}$B($p,α$)$^7$Be reaction in the $E_p=1.028-0.630$ MeV bombarding energy domain.

Proton beams at bombarding energies $E_p=0.630-1.028$ MeV were delivered by the tandem accelerator of the Laboratorio dell’Acceleratore (LdA) at Federico II University of Naples [32]. The energy step here used was about 40 keV. To reduce pile-up effects, in this experiment the beam intensity did not overcome 1 nA. A boron foil (38 µg/cm$^2$ thick) was used as reaction target. The target surface was orthogonal to the beam direction. Because of the manufacturing process, the target includes several contaminants (mainly Li, C, O, Al, Cl, Cu, Ba). Due to kinematic and energy loss reasons, peaks due to the heavier of these contaminants overlap with the $α_0$ signal at backward angles. For this reason, to measure these yields we used a method based on the simultaneous measurements of two ejectile spectra at the same angle (in opposite directions with respect to the beam axis), the first one taken with an unshielded silicon detector, the second one taken by a silicon detector covered by a thin Al foil (3µm thick). This foil is able to stop (or highly slow down) the $α_0$ particles, allowing the elastically scattered protons to punch through. Then, the $α_0$ yields have been derived by subtraction, taking into account the energy loss and straggling effects. Details on this experimental technique are described in [33, 34].

With this experimental setup we were able to extract the angle-integrated reaction cross section; the corresponding $^{10}$B($p,α$)$^7$Be $S$-factor is shown in Figure 1, as black dots. Our data are ≈30% lower than the estimates based on Roughton et al. data [20], even if they agree within the error bars. Consider that in the data of Ref. [20] also the contribution given by the $α_1$ decay channel is included; anyway, at energies lower than 0.8 MeV, it is of the order of some percent. Vertical bars represent statistical errors; non statistical errors amount to 5.3% and derive from the internal normalization procedure. In Figure 1 we show also results derived from differential cross section taken from the literature. In particular, we used data reported by Brown et al [35] (squares, normalized to our cross section scale), by Cronin [36] and by Overley and Whaling [37]. Considering this comprehensive data set and including also the differential cross section for the $^{10}$B($p,ν$)$^{10}$B elastic scattering [38, 39] and $^{10}$B($p,α_1$)$^7$Be$^*$ reaction [36] data, we performed a simultaneous $R$-matrix fit of data, with the aim of improving our knowledge of $^{11}$C structure. The result of the fit is reported in Figure 1 as solid line. It reproduces quite reasonably the
overall data trend only if the presence of a state at 9.36 MeV in $^{11}$C level scheme is included, as discussed in details in Ref. [34]. The comparison of angular distributions with $R$-matrix calculations, that is discussed in details in Ref. [34], suggests a possible $5/2^-$ assignment for this state.

3. The $^{19}$F(p,α₀)$^{16}$O reaction in Nuclear Structure and Astrophysics

The study of low energy $^{19}$F(p,α₀)$^{16}$O reaction allows to investigate the structure of the $^{20}$Ne compound nucleus, that can show important α-cluster structures [40]. Anyway, several ambiguities in the $^{20}$Ne spectroscopy still persist [22], especially in the lowermost energy region accessible with direct measurements ($E_p < 0.5$ MeV). Furthermore, this reaction is involved in the nuclear astrophysics domain for two reasons. First, it closes the CNOF cycle in the hydrogen-burning phase of massive stars [41]; second, it can be an important fluorine destruction channel in hydrogen-rich stellar environments [27]. Unfortunately, because of the lack of direct low-energy data reported in the literature, the reaction rate estimate at astrophysical energies, based on high-energy extrapolations, is characterized by large uncertainties [18]. Recent indirect data obtained with the Trojan Horse Method pointed out the important role played by a low energy resonance at 113 keV [28, 29]. Considering the importance of this reaction and taking into account the lack of data reported in the literature, we performed two separate experiments at LdA in Napoli ($E_p \approx 0.6$-1.0 MeV) and at INFN - Laboratori Nazionali di Legnaro ($E_p \approx 0.2$-0.65 MeV) aimed at measuring excitation functions and angular distributions of the $^{19}$F(p,α₀)$^{16}$O reaction in wide (low) energy domain. The details of these experiments and on the devices used for particle detection have been widely discussed in Refs. [24, 26].

The $^{19}$F(p,α₀)$^{16}$O integrated cross section $\sigma(E)$ have been transformed in the astrophysical $S$-factor, that is shown in Figure 2 as green stars (high energy part of the data set, experiment performed in Napoli) and black triangles (low energy part of the data set, experiment performed in Legnaro). The open triangles, blue diamonds and magenta circles are the result of older direct
Figure 2. $S$-factor of the $^{19}$F($p, \alpha$)$^{16}$O reaction at low energies ($\lesssim 1$ MeV). Black triangles: experimental data obtained in the Legnaro experiment (vertical bars: statistical errors; azure band: non-statistical errors) [26]. Green stars: data obtained in the Napoli experiment [24]. Light blue triangles: data by Isoya et al [42]. Blue diamonds: data reported by Caracciolo et al [43]. Magenta circles: data by Breuer [44]. Red solid line: $R$-matrix fit of experimental data obtained in the Legnaro and Napoli experiments [24, 26].

measurements [42, 43, 44], as reported in the NACRE paper [18]. The blue band represents non-statistical errors of the Legnaro experiment, estimated as discussed in Ref. [26]. The results of the two experiments performed in Napoli and Legnaro are in agreement (within the errors) in their overlap region. The inspection of the low energy part of Figure 2 indicates a behaviour of the $S$-factor that can be attributed to the sum of a direct component and of various resonances of the compound nucleus. An important resonant contribution is due to a broad $2^+$ state at 0.251 MeV ($E_x=13.095$ MeV, $\Gamma=162$ keV); this finding is in agreement with considerations made on the angular distributions in Ref. [26]. The red line represents the result of a $R$-matrix fit on the experimental data. The resonance parameters used are reported in detail in Ref. [26]. We included in this fit procedure the presence of a $2^+$ state at 0.113 MeV as suggested by an experiment done with the Trojan Horse Method [28, 29]. The interference effect between the two close-lying $2^+$ states explains the asymmetric high energy tail for the 0.251 MeV $2^+$ state pointed out by the experimental data.

The low-energy $S$-factor extrapolated via the $R$-matrix fit is $\approx 1.5$-2 times larger than the corresponding NACRE evaluation based on the non-resonant extrapolation of high energy data. As a consequence, also the reaction rate is well larger than the NACRE predictions, as discussed in Ref. [26]. This larger reaction rate could lead to a more efficient fluorine destruction in extra-mixing phenomena. This finding is in agreement with recent experimental observations of fluorine abundance in metal-poor AGB stars [27, 45]; therefore, it could contribute to improve the description of fluorine nucleosynthesis in stars [46].

4. Summary
In these proceedings we discuss briefly the results of two experiments concerning the study of the $^{10}$B($p, \alpha$)$^7$Be and $^{19}$F($p, \alpha$)$^{16}$O reactions at energies near or below the Coulomb barrier.
Their analysis allows to refine the spectroscopy of the formed compound nuclei, i.e. $^{11}$C and $^{20}$Ne respectively. For the $^{11}$C case, a comprehensive $R$-matrix fit of the $^{10}$B($p,\alpha_0$)$^7$Be $S$-factor and of other reaction and scattering channels suggests the presence of an unreported excited state at $E_x \approx 9.36$ MeV, with tentative $J^\pi = 5/2^-$ assignment [34]. Concerning the analysis of the $^{20}$F($p,\alpha_0$) reaction, we improved the spectroscopy of $^{20}$Ne excited states in the $E_x \approx$13-14 MeV domain, as widely discussed in Refs. [24, 26]. Furthermore, we pointed out the role played by low energy resonances (and their interferences) in the $S$-factor, resulting in a calculated reaction rate at temperatures typical of AGB stars well larger than the commonly adopted extrapolations based on high energy data; this finding seems in the right direction of recent experimental observations of fluorine abundance in metal-poor AGB stars and can be useful to improve our knowledge of fluorine nucleosynthesis in stars.

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