Study of highly excited states in ^{16}O with ^{3}He+^{13}C reactions at low energies

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Abstract. We report some preliminary experimental results on ^{13}C(^{3}He,α)^{12}C reactions at low bombarding energies, in the range 1.4 – 2.2 MeV. The reconstruction of kinematic quantities in the final channel was performed by using a high-performance, low-threshold hodoscope, allowing for the particle identification even for low energy ejectiles. We succeeded in measuring detailed angular distributions, in absolute values, even for the transition leading to the emission of ^{12}C in the Hoyle state, then resulting into 4 α particles in the final channel. The analysis of angular distributions as a function of energy suggests the occurrence of two low-spin resonant states, respectively with $J^{\pi} = 1^{-}$ and 2^{+}, at excitation energies of $\approx$ 24.1 and 24.5 MeV.

1 Introduction

The study of the structure of self-conjugate nuclei attracted lot of interest in recent times [1, 2]. The occurrence of pronounced α clusters effects close to the Nα disintegration threshold can represent an unique tool to understand the behaviour of long-range correlations in nuclear forces that are responsible of several exotic internal re-arrangement of nucleons. Furthermore, several theoretical works based on $ab-initio$ calculations [3], molecular dynamics approaches [4] and algebraic models [5], explored the structure of light self-conjugate nuclei and suggested the occurrence of cluster structures characterized by specific geometrical arrangements. For example, a triangular-like structure is expected for the famous Hoyle state in ^{12}C [6], for which the topology of the decay into three α particles could bring information

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on the occurrence of exotic phenomena as Bose-Einstein condensate formation in nuclei [7–10]. Furthermore, the application of Algebraic Cluster Model (ACM) predictions based on symmetry considerations in nuclear structure leads to a very good description of the sequence of excited states in ^{12}C, ^{16}O and ^{20}Ne, again reinforcing the idea of strong clusterization effects occurring in such nuclei [11]. Sizable contributions of highly clusterized states to the rate of astrophysically interesting reactions have been also recently discussed in the literature [12, 13].

Clustering could affect also the structure of neutron-rich isotopes of Be, C, O, Ne (see, e.g., [14–16]). In this case, the additional neutrons can play the role of covalence particles, in analogy with the theory of the molecular bonding [17, 18]. Several calculations adopted a Molecular Orbital approach that was able to reproduce the sequence of low energy states and also the form factors and electromagnetic transition strengths of such nuclei.

In general, this rich phenomenology was derived in the last decades also thanks to the development of very sophisticated detectors (with a large coverage of the solid angle [19–25], a good granularity [26–28], the smart use of several identification techniques [29, 30], and excellent energy resolution) and by using several analysis tools (as *R*-matrix, invariant and missing mass techniques, particle-particle energy and angular correlations, see e.g. [31]).

Despite the success of the cluster models in describing the structure of light nuclei, several obscure points still need to be understood. In particular, even for the self-conjugate nuclei, the spectroscopy of very highly lying states (i.e., above 15-20 MeV excitation energy, just to give a reference) is still uncertain, as indicated, e.g. in the compilations of nuclear spectroscopy data [32]. The poor knowledge of the spectroscopy of high-lying states often represents a limit in the comparisons between models and data. For example, the ACM predicts the existence of cluster states at high energies in ^{12}C and ^{16}O that are still unexplored from the experimental side [5], and whose existence would represent a strong confirmation of the validity of the model. Another very interesting comparison could come from the prediction of the quartet model of Ref. [33]: in this framework, cluster states with very low spin (and natural parity) are predicted to occur also at high energies because of the promotion of a quartet of nucleons, behaving as an α-like particle, to an outer orbital of an average potential well where the alpha particles can be situated. In particular, for the case of ^{16}O, Ref. [33] predicted the existence of several quartet states at excitation energies above 23 MeV.

To improve our knowledge on the spectroscopy of ^{16}O states at high energy, it could be interesting to perform a high *Q*-value nuclear reaction with low bombarding energies, allowing the formation of the ^{16}O compound nucleus at very high excitation energies, with some selectivity towards states with low spin. In this framework, the ^{3}He+^{13}C → ^{4}He+^{12}C reaction at very low bombarding energies (e.g., well lower than the Coulomb barrier, at about 2.8 MeV) can represent a useful tool, because of its very high Q-value, 22.793 MeV. The high Q-value allow also to populate, in the exit channel, several excitation states of the ^{12}C residual nucleus, including the very interesting transition leading to the ^{12}C in the Hoyle state, and therefore to the presence of four α particles in the final channel.

From the experimental point of view, very few data are available in the literature. In particular, they have been mainly obtained at moderately-high energies, where more direct reaction mechanisms are typically favoured as opposed to the formation of a compound nucleus [34–37]. In particular, Kellogg and Zurmuhle [34] studied the reaction at 12, 15 and 18 MeV, proposing a direct pick-up mechanism to describe the trend of angular distributions. Interestingly, in Ref. [35] it is suggested that, because of the peculiar configuration of ^{12}C in the Hoyle state, the ^{13}C(^{3}He,α_2)^{12}C transition would require the compound nucleus formation, being very difficult to be explained by a simple pick-up process.

In the low energy side, Ref. [38] reported the differential cross section for the ^{13}C(^{3}He,$\alpha_{0,1}$)^{12}C channels, but with a relatively low accuracy (25%) and at only one bombarding energy, 2.00 MeV. In a subsequent paper [39], the authors reported data in relative units for angular distributions of the α_0 and α_1 channels at the bombarding energy of 4.50 MeV. In a paper from the late '60s [40], it is clearly indicated that the influence of the ^{16}O structure is essential to study the ^{3}He induced reaction on ^{13}C from 5 to 8 MeV. The analysis of excitation functions of ^{13}C(^{3}He,α_0)^{12}C as well as ^{13}C(^{3}He,^{3}He)^{13}C and ^{13}C(^{3}He,p)^{15}N was performed to inspect a resonant structure at around 6.0 MeV bombarding energy. The most recent data come from Ref. [41], where the ^{13}C(^{3}He,$\alpha_{0,1}$)^{12}C reactions are studied at E_{cm} = 1.20 and 1.05 MeV. In this case, angular distributions were interpreted by assuming a direct scenario where two different mechanisms could compete: a heavy-particle stripping (^{9}Be) or a neutron pick-up [41]. Unfortunately, no data for the α_2 were reported in these works.

To better address the question of nuclear spectroscopy in ^{16}O at high excitation energies, we performed a new experiment of ^{13}C(^{3}He,α)^{12}C reactions at low energies by means of a new hodoscope, OSCAR, used in its full geometrical configuration. The preliminary results on the measurement of excitation functions and angular distributions of absolute cross sections are reported in the following Sections, together with a preliminary Legendre polynomial analysis of angular distributions aimed at determining the spin-parity assignments for two broad states ^{16}O in the excitation energy region $\approx 21 - 22$ MeV.

2 Experimental setup

The experiment was performed at the AN2000 van de Graaf accelerator at the Laboratori Nazionali di Legnaro, Italy. Singly-charged ^{3}He beams with energies varying form 1.4 to 2.2 MeV bombarded 99% enriched self-supporting ^{13}C targets, with a thickness of 29 μg/cm^2. The beam intensity ranged from 70 to 190 nA; the beam energy was varied in $\approx$ 20 keV steps. The beam was stopped inside a long Faraday cup, and the current was integrated by a digital module, resulting into an overall uncertainty on the accumulated charge of $\approx$ 3%. We directly measured the charge status of the beam after passing the target at all the bombarding energies here explored. The target holder and the detection system OSCAR were placed inside a chamber with a vacuum pressure in the order of 10^{-6} mbar.

The four detection modules of the OSCAR array (hOdoscope of Silicons for Correlations and Analysis of Reactions) were made by a new-generation hodoscope, based on two segmented detection stages (20 μm Single Sided Silicon Strip Detector (SSSSD) - 500 μm Silicon pads). Each module was characterized by an excellent energy resolution and high versatility for its compactness [42]. The SSSSD is made of a thin silicon wafer, whose electric contact on the front surface is segmented into 16 aluminum vertical strips having a width of 3 mm, and an inter-strip of about 0.125 mm. 16 electric lines leave the silicon surface through a ceramic frame and connect to a charge-sensitive pre-amplifier that is placed very close to the detector to reduce the noise. The silicon is polarized with typical bias voltages of 3.0 V. The second detection stage is made of 16 silicon pads on a ceramic support, each with an active area of 1 cm^2. The pads are welded to a printed circuit board which is connected to a second board containing the pre-amplifiers. The whole design of the electronic board was optimized to minimize cross talk effects and electronic noise.

During the experiment, an array of 4 OSCAR telescopes was used. *OSCAR Blu* and *OSCAR Verde* covered the forward angles, while *OSCAR Nero* and *OSCAR Rosso* were positioned before the target to cover the backward angles, as can be seen from Figure. 1. Two of the telescopes (*OSCAR Verde* and *OSCAR Rosso*) have only one stage consisting of 16 silicon pads. To avoid a large flux of elastically scattered particles impinging on the detectors, suitable mylar or aluminium absorbers were positioned at the entrance windows of the telescopes.

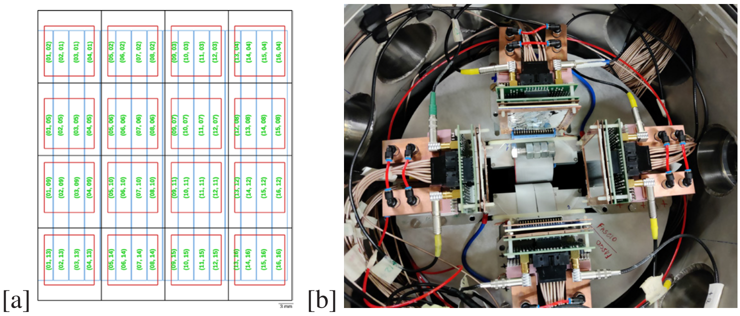

Figure 1. OSCAR geometry. (a) A schematic view of a two layer OSCAR telescope's layout where each pseudo-detector is indicated as (pad,strip) combination [42, 43]. (b) Setup of the HELICA experiment with four OSCAR pseudo-telescopes.

As seen in Figure 1, the geometry of *OSCAR* is determined by the possible intersections of the 16 strips with 16 pads, which make a total of 64 combinations, each one indicated as a *pseudo-telescope*. The positioning of the hodoscopes was carefully performed, with submillimeter accuracy. All the data on geometries and positioning were used to perform careful Montecarlo simulations of the whole apparatus; in this way it was possible to estimate the central polar and azimuthal angles and the solid angle associated to each pseudo-telescope; the accuracy of solid angle determination was $\approx 3\%$. The used front-end electronics was made by compact 16-ch NIM modules allowing for the signal amplification and trigger generation. The ADC conversion was performed by using the FAIR [44] acquisition system.

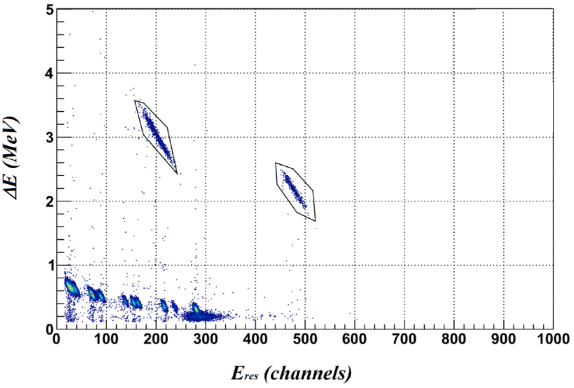

Figure 2. An example of ΔE-E correlation plot for a pseudo-telescope placed at backward angles. α and proton loci are clearly distinguished. The α particles coming from the ^{13}C(^{3}He,α_0)^{12}C and ^{13}C(^{3}He,α_1)^{12}C* reaction channels are evidenced in the black contours.

Careful calibration of the two stages of the apparatus were performed both by using elastically scattered proton beams of low energies and also by using α sources; both calibration showed excellent linearity. Changes in the gain of the electronic chain were taken into account by using dedicated pulser runs. An example of the good particle identification obtained from of a typical ΔE-E matrix associated to a given pseudo-telescope is shown in Figure 2.

The good separation between 4He and protons is evident. This allowed to cleanly extract the yields associated to the ejectiles characterizing a given reaction channel.

3 Data analysis

Absolute cross sections for the ^{3}He+^{13}C → ^{4}He+^{12}C reaction channels were determined by direct counting of the yields (after background subtraction) of the peaks associated to each transition, by considering the areal density of the target, the solid angles subtended by each pseudo-telescope and the integrated beam current. The overall non-statistic errors on absolute cross section scales obtained with this procedure are about 8%. The preliminary cross section scale here obtained is not far from the ones reported by [38, 39] at 2 MeV, and also similar to the [41] data at 1.4 MeV. In all the cases, the shapes of the angular distributions for the α_0 and α_1 channels obtained in the present work are quite similar to the ones reported in the literature [38, 41]. We succeed in measuring also the cross sections of the α_2 channel at angles in the forward hemisphere. Preliminary results indicates shapes of the angular distributions that are similar to the higher energy data reported in Ref. [40]. They will be the subject of accurate future analysis, because of the possible link of this decay channel with highly clustered structures in ^{16}O.

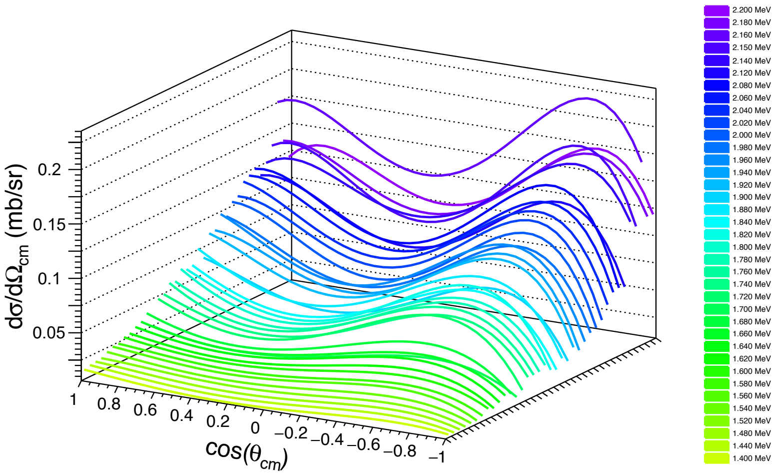

Figure 3. Evolution of the trend of angular distributions for the ^{13}C(^{3}He,α_1)^{12}C* reaction channel leading to the 4.44. MeV state in ^{12}C.

An example of the evolution of the shape of angular distributions as a function of the bombarding energy is shown in Figure 3. Apart from the obvious average lowering of the absolute cross section scale with decreasing energies (effect due to the Coulomb barrier penetration) a continuous change of shape is evident, that could indicate the presence of broad states with different spin and parities. This qualitative finding was explored in more detail by analyzing the angular distributions for the ^{13}C(^{3}He,α_0)^{12}C channel: the presence of two 0^+ particles in the outgoing channel (^{4}He and ^{12}C) allows a direct assignment of J^π of a resonance in the compound nucleus by inspecting the trends of the coefficients of the Legendre polynomial expansion of the measured angular distributions (see also [45–47]). Preliminary analyses of this type performed on the experimental data seem to indicate the occurrence of two broad (≈

300 keV) states, with $J^\pi = 1^-$ and 2^+, at excitation energies respectively close to 24.1 MeV and 24.5 MeV. Interestingly, some hints on the existence of broad states close to both such energies have been reported in the literature [32], but with just tentative or no information of the spin and parity. We plan to improve our knowledge on such states by means of detailed *R*-matrix fits of the experimental data, that are currently ongoing.

Finally, we started the investigations of the branching ratio between the ground state transition and the Hoyle-state transition in the ^{13}C(^{3}He,α)^{12}C channels here studied. In a qualitative fashion, in fact, we could expect that a state characterized by having a strong cluster structure in the ^{16}O compound nucleus should preferentially decay by emitting an α particle and leading to the ^{12}C in the Hoyle state. This would imply that the reduced partial width $\gamma^2_{\alpha_2}$ should be larger than the $\gamma^2_{\alpha_0}$ and $\gamma^2_{\alpha_1}$ partial widths. Signals of some anomalies going in this sense have been found, in the preliminary analysis of the experimental branching ratios, for the state at around 24.5 MeV; further analysis are currently ongoing to deepen this interesting finding.

4 Conclusions

We discussed some preliminary results of a new experiment on the study of low energy ^{3}He+^{13}C reactions. It was possible to populate the self-conjugate nucleus ^{16}O in low spin states with very high excitation energies, a region where the existence of α-like states have been predicted by theoretical models. In particular, the transmutations leading to the ^{4}He+^{12}C outgoing channels are of large importance, because they could signal the occurrence of this type of clusterization in the parent nucleus. In this framework, we succeeded in measuring the absolute cross sections of angular distributions leading to the ^{12}C in the ground state, in the first excited state and, for the first time in this energy region, in the Hoyle state. The preliminary analysis of such experimental data point out the presence of two broad states at around 24.1 and 24.5 MeV, having different spin and parities. The branching ratios of the ground state vs. Hoyle state transitions suggest some interesting effects that will be the subject of future investigations.

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