Four α-particles as a final state of ^{16}O* Quasi Projectile decay

Maria Vittoria Managlia[1], *Mauro* Bruno[1,2], *Michela* D'Agostino[1,2], *Luca* Morelli[1,2], *Giorgio* Baiocco[3], *Francesca* Gulminelli[4], *Catalin* Frosin[5,6], *Sandro* Barlini[5,6], *Antonio* Buccola[5,6], *Alberto* Camaiani[5,6], *Giovanni* Casini[6], *Magda* Cicerchia[7], *Marco* Cinausero[7], *Daniela* Fabris[8], *Fabiana* Gramegna[7], *Giorgia* Mantovani[7], *Tommaso* Marchi[7], *Pietro* Ottanelli[5,6], *Gabriele* Pasquali[5,6], *Silvia* Piantelli[6], and *Simone* Valdré[6]

[1]Dipartimento di Fisica e Astronomia dell'Università di Bologna, Italy.
[2]INFN Sezione di Bologna, Bologna, Italy.
[3]Dipartimento di Fisica dell'Università, Pavia, Italy.
[4]Normandie Univ. ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, 14000 Caen, France.
[5]Dipartimento di Fisica e Astronomia dell'Università di Firenze, Italy.
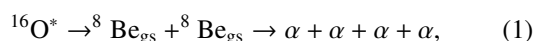[6]INFN Sezione di Firenze, Firenze, Italy.
[7]INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy.
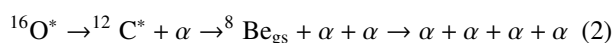[8]INFN Sezione di Padova, Padova, Italy.

Abstract. Four α-particles as a final state of ^{16}O* quasi-projectile decay produced in peripheral ^{16}O+^{12}C reactions at 130 MeV is thoroughly studied. The different decay channels leading to the four α-particles final state are reconstructed by carrying out an event-by-event analysis of α correlations in the population of intermediate ^{8}Be and ^{12}C. Although small, a non negligible contribution due to ^{8}Be$_{gs}$ evaporation is found. A comparison between predictions of an accurate Hauser-Feshbach decay code and branching ratios of the different decay channels is performed. Significant deviations are observed, among these the Hoyle state population which is considerably lower than the one predicted according to the statistical model, thus suggesting possible structure effects in the Coulomb barrier and/or in the transmission coefficients.

1 Introduction

The aim of this experimental campaign carried out by the NUCL-EX collaboration is investigating the properties of light nuclei [1]. In this contribution we will present results of peripheral ^{16}O+^{12}C collisions with the decay of the excited ^{16}O* Quasi Projectile (QP) in a final state of four α-particles. A comparison with the predictions of a statistical decay code (HFℓ) based on Hauser-Feshbach formalism and including all the discrete levels of light nuclei, taken from the NUDAT2 database [2], was made. Agreement or disagreement with statistical decay code could be a hint of the importance of non statistical effects. The analysis explores the two channels of the decay [3]: the first foresees the formation of two ^{8}Be$_{gs}$ which both decay in two α particles

$$^{16}\text{O}^* \rightarrow\, ^8\text{Be}_{gs} +\, ^8\text{Be}_{gs} \rightarrow \alpha + \alpha + \alpha + \alpha, \quad (1)$$

the second consists in the emission of an α-particle leaving a ^{12}C* as a residue, which in turn decays in three α-particles, through a ^{8}Be intermediate state.

$$^{16}\text{O}^* \rightarrow\, ^{12}\text{C}^* + \alpha \rightarrow\, ^8\text{Be}_{gs} + \alpha + \alpha \rightarrow \alpha + \alpha + \alpha + \alpha \quad (2)$$

where ^{12}C* can be in the Hoyle state (0^+_2, 7.65 MeV) [4] or in a 3^- excited state at 9.64 MeV.

2 The experiment and the event selection

Measurements were carried out at the INFN laboratories in Legnaro using a pulsed beam of ^{16}O at 130 MeV [5]. The apparatus consists of GARFIELD, a multi-detector located inside a large scattering chamber, coupled with the Ring Counter (RCo), a three-stage annular detector with a truncated cone geometry aimed for the detection at forward angles [6]. ΔE-E correlation and fast-slow PSA techniques were used for particle identification. The selection of events of interest has been performed by considering only events which feature four α-particles, in the final state, detected at forward angles (by the RCo in $5° \div 17°$ angular range) and no product detected by GARFIELD ($30° \div 150°$).

3 Analysis

From energy and momentum conservation one obtains the target and projectile excitation energy:

$$E_{tot_i} = E_{beam} = E_{tot_f} = \sum_{i=1}^{4} E_{\alpha_i} + E_{rec} + E_{exc_t} - Q \quad (3)$$

where E_{α_i} is kinetic energy of the ith α-particle, E_{exc_t} the QT excitation energy, Q is the reaction Q-value and E_{rec} is the QT recoil energy.

Taking into account also the energy loss in the target, E_{rec} turns out to be always lower than the threshold for ^{12}C detection.
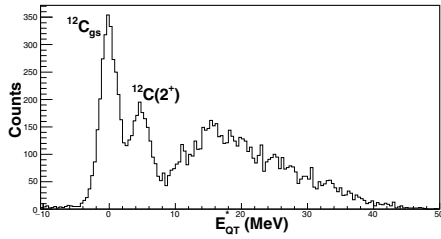

Figure 1. QT excitation energy as calculated in eq. (3).

In the energy spectrum of the QT, shown in Fig. 1, it is possible to observe the corresponding peaks at the ground state and first γ excited state at 4.4 MeV of the QT (^{12}C) nucleus. A tail to higher excitation energies can be seen as well. The analysis presented here includes only the events in which the QT remains in its ground state. However, other analyses that consider the other QT excitation energies have been carried out [7]. In order to determine the decay channel in two ^{8}Be$_{gs}$, the relative energy of the pair of α-particles providing the lowest value out of the four is considered together with the relative energy of the two complementary α-particles. The vertical red lines in Fig. 2
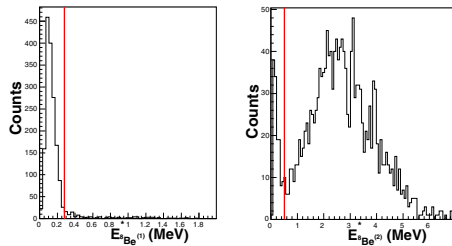

Figure 2. Left panel: minimum relative energy of couples of α-particles. Right panel: relative energy of the complementary couple.

represent the selection performed in order to consider the two relative energies corresponding to the ground state of the ^{8}Be. In this way, only events with the production of two contemporary ^{8}Be$_{gs}$ are taken into account. This accounts for 7.5 % of the total number of events with the QT in the ground state.

To consider the events corresponding to the second decay channel, from the excitation energy of three α-particles out of the four, the excitation energy of carbon is calculated as the minimum energy of the four combinations. This amount is added to the energy of the fourth α particle to obtain the excitation energy of the ^{16}O.

In Fig. 3 we show the excitation energy of the ^{12}C*. The two excited carbon states (Hoyle 0_2^+ and 3^- state, labelled as C$_1^*$ and C$_2^*$) can be distinguished. The selection of the data that fall within the 7.65 MeV or 9.64 MeV peaks enables a separate analysis of the two decay

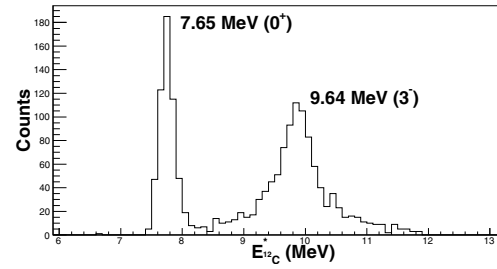channels in which an excited carbon nucleus is formed.

Figure 3. Excitation energy spectrum of ^{12}C* in which ^{16}O* decays with the emission of an α particle.

The decay process with the formation of ^{12}C in the Hoyle state accounts for 32 % of the occurrences, whereas the one with carbon in 3^- state represents 49 %. This results in the preferential decay of ^{16}O* through these decay channels.

Finally, we have performed the comparison with the HFℓ predictions where we considered the decay of a mixing of excited levels with characteristics extracted from experimental data. Table 1 shows the results of this comparison: the observed branching ratios differ significantly

Table 1. Experimental branching ratios of different reactions compared to HFℓ predictions. C$_1^*$ corresponds to the Hoyle state, C$_2^*$ to 9.64 MeV.

reaction	EXP.(%)	HFℓ (%)
^{12}C(^{16}O,^{8}Be$_{gs}$+^{8}Be$_{gs}$)^{12}C$_{gs}$	7.5	20.8
^{12}C(^{16}O,^{12}C$_1^*$ + α)^{12}C$_{gs}$	32.0	53.0
^{12}C(^{16}O,^{12}C$_2^*$ + α)^{12}C$_{gs}$	49.0	19.3
background	11.5	6.8

from the theoretical ones, especially as far as Hoyle state is concerned. A possible explanation might be the influence of the well-known α-cluster structure of the Hoyle state on the Coulomb barrier and the associated transmission coefficients of the corresponding evaporation channel.

References

[1] L. Morelli *et al.*, J. Phys. G 41, 075107 (2014). L. Morelli *et al.*, J. Phys. G 41, 075108 (2014). L. Morelli *et al.*, J. Phys. G 43, 045110 (2016), F. Gulminelli *et al.* in **Nuclear Particle Correlations and Cluster Physics** ed. U. Schroeder, p 257, L. Morelli *et al. ibid* p.283.

[2] *www.nndc.bnl.gov/nudat2/*.

[3] M. Freer *et al.* Phys. Rev C **51**, 1682 (1995).

[4] F. Hoyle *The Astrophysical Journal, Supplement Series* **1**, 12 (1954).

[5] C. Frosin, **Thesis: The ^{16}O+^{12}C reaction at 90.5, 110 and 130 MeV beam energy**, University of Bologna, 2016.

[6] M. Bruno *et al.*, Eur. J. Phys. A 49, 128 (2013).

[7] M. Bruno *et al.* submitted to J. Physics G.