EPJ Web of Conferences **324**, 00013 (2025) https://doi.org/10.1051/epjconf/202532400013
NSD2024

Alpha structure of ^{16}O at high excitation energy via ^{3}He + ^{13}C nuclear reactions

Ivano Lombardo[1,2,*], *Luigi* Redigolo[1,2], *Daniele* Dell'Aquila[2,4], *Mariano* Vigilante[2,4], *Mualla* Ayketin[5], *Lucia* Baldesi[6,7], *Sandro* Barlini[6,7], *Alberto* Camaiani[6,7], *Giovanni* Casini[6,7], *Caterina* Ciampi[6,7], *Daniela* Fabris[8], *Magda* Cicerchia[5,8], *Catalin* Frosin[6,7], *Fabiana* Gramegna[9], *Tommaso* Marchi[9], *Antonio* Ordine[6,7], *Pietro* Ottanelli[6,7], *Gabriele* Pasquali[6,7], *Silvia* Piantelli[7], *Marco* Russo[1,2], *Andrea* Stefanini[6,7], *Simone* Valdrè[7], and *Giuseppe* Verde[2]

[1]Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Via S. Sofia, Catania, 95123, Italy
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Via S. Sofia, Catania, 95123, Italy
[3]Dipartimento di Fisica "E. Pancini", University of Naples Federico II, Via Cintia, Naples, 80126, Italy
[4]Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Via Cintia, Naples, 80126, Italy
[5]Dipartimento di Fisica e Astronomia, University of Padova, Via Marzolo, Padua, 30020, Italy
[6]Dipartimento di Fisica, University of Firenze, Via G. Sansone, Sesto Fiorentino (FI), 50019, Italy
[7]Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Via G. Sansone, Sesto Fiorentino (FI), 50019, Italy
[8]Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Via Marzolo, Padua, 30020, Italy
[9]Istituto Nazionale di Fisica Nucleare, Lab. Nazionali di Legnaro, Via dell'Università, Legnaro (PD), 35020, Italy

Abstract. These proceedings report a new data analysis aimed to the study of low-spin, high excitation energy states in the spectroscopy of the ^{16}O nucleus around 24 MeV excitation energy. After a careful spectroscopical analysis, based on the Legendre polynomials decomposition of angular distribution data obtained in ^{3}He+^{13}C reactions at low energies, it was possible to determine the J^π assignments for two high-lying states at $E_x \approx 24.1$ and ≈ 24.5 MeV. Some conclusions are also drawn regarding the presence of pronounced 4α structure of these states, based on the analysis of the branching ratios of the α_2 to the α_0 channels in the ^{16}O compound nucleus decay.

1 Introduction

It is well known that some light nuclei may exhibit peculiar structures, quite different from the classical spheroidal configurations; while nuclei with a large excess of neutron (such as ^{6,8}He, ^{11}Li, ^{20}C) are often characterized by a compact nucleonic cores surrounded by a neutron halo or a neutron skin, the self-conjugate ones (those having even and equal numbers of neutrons (N) and protons (Z), i.e. ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg...), may be characterized, in their ground or excited states, by the presence of clusters fundamentally similar to α-particles [1–10]; this would occur given the high binding energy of the ^{4}He nucleus and its complete saturation of spin and isospin. Among the various possible excited states, a particularly important role is played by the so-called "Hoyle-like states", that are expected to occur in the aforementioned self-conjugate nuclei close to the Nα disintegration thresholds. The study of these phenomena may help to shed light on the existence of the *long-range* correlations present in the nuclear force [11].

In this context, the spectroscopy of the ^{16}O nucleus is rather interesting, being it a doubly-magic *and* self-conjugate nucleus: these characteristics lead to a quite low level density, with respect to those of neighboring even-even nuclei. Furthermore, the first particle separation threshold is that of the ^{12}C + α channel, at $E_x = 7.16$ MeV, significantly lower than the single nucleon (p, n) or other particle decays $(^2H, ^3He, ^3H)$, which all occur at $E_x > 10$ MeV [12].

Several are the models predicting that the ^{16}O nucleus structure may evolve as a function of the energy, from a very compact spherical (or tetrahedral) arrangement of 4α particles for the ground states, until the subsequent development of cluster features near the α threshold, and then eventually reaching very broad structures of 4 weakly-interacting α-like particles at energies near the 4α decay threshold ($\approx$14.4 MeV) [13–17]. However, despite recent experimental efforts, it is still difficult to unambiguously locate an analogue of the Hoyle in this energy zone [18–20].

The situation is even less clear at higher excitation energies, where only very few theoretical models try to forecast the existence of 0^+ and other low-spin natural parity excited states, with potential cluster nature, at energies higher than 20 MeV [21]. In this context, although the existence of some 0^+ excited states was predicted in the 23-26 MeV excitation energies regime, only few studies and experimental results are available for low-J^π states in this region. In the past year, upon the hypothesis of the presence of some cluster component in high-energy

*e-mail: ivano.lombardo@ct.infn.it

^{16}O states, these were studied by various research groups [22, 23] through refined four α particles coincidence measurements. Among the various decay channels, the one populating α plus a ^{12}C excited in the Hoyle state is very promising to unveil the potential cluster structure of the parent state, but the experimental situation is still unclear.

The aim of the present work is to study the occurrence of high-energy and low J^π states in the ^{16}O nucleus. To selectively study these states, it is useful to choose a two-body reactions with high separation energy in the entrance channel and low center-of-mass energy: the low values of relative energies would imply the occurrence of small values of orbital angular momentum in the initial channel (ℓ_{in}). For this reason we performed experiments on ^{3}He + ^{13}C reactions at low energies, allowing to study the *golden channel* leading to the decay of the ^{16}O compound nucleus into an α particle and a residual ^{12}C excited in the Hoyle state. This would represent a direct, albeit not simple, way to access this four-body decay channel. Up to date, only few data are available for this type of reaction at low energies (< 3 MeV), mainly because it is difficult to discriminate the emitted α particles among the other reaction products. The experimental investigations are complicated also because the Coulomb Barrier has a value of $U_c \approx 2.8$ MeV, hindering the cross section values in the low energy regime here explored.

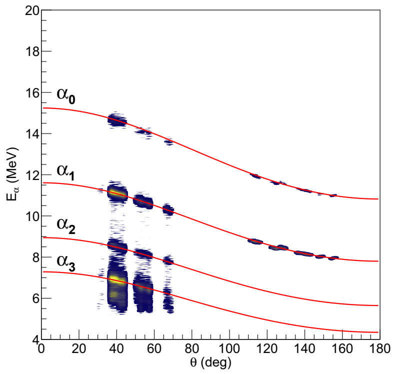

Figure 1. Kinematic plots of well identified α particles emitted in ^{3}He + ^{13}C collisions at ≈2 MeV and detected by the OSCAR array.

2 Experimental procedure

The HELICA experiment was performed in 2021 at the AN2000 Van de Graaf accelerator at Laboratori Nazionali di Legnaro (Italy), accelerating single-charged ^{3}He$^+$ beams at energies between 1.4 and 2.2 MeV and scanning the excitation functions with a 20 keV energy step. The beam energy resolution was better than 0.5 keV; the current of the beam was maintained at around 100 nA, and the experiment was performed by driving the beam on ^{13}C thin self-supporting targets with an enrichment level of 99%. The (very compact) detection system was composed by four OSCAR units [24], arranged together with the target holder, the 96 front-end electronics channels and the cooling system within a very small vacuum chamber (≈30 cm diameter). The detection system featured high granularity ($\Delta\theta \approx 2^o$) on full coverage of the polar angles, granted by the 128 $\Delta E - E$ pseudo-telescopes made by the first and the second stages of the OSCAR detectors, respectively of 20 and 500 μm thick. Thin absorbers of different materials were also used, for some part of the measurements, to stop the large flux of elastically scattered ^{3}He particles. The system was able to exploit its very low identification threshold and high energy resolution (the observed effective identification threshold for α particles are around 1.5 A.MeV, while ≈70 keV energy resolution was achieved), which led to the unambiguous identification of several concurrent decay channels in the ^{3}He + ^{13}C reactions.

3 Preliminary results

In the present work, the unambiguous identification of the investigated decay channels was achieved by the combination of the $\Delta E - E$ technique and the consequent analysis of kinematic loci for well identified α particles. An example of kinematic loci is shown in Fig. 1; experimental data are superimposed, with excellent agreement, on two-body kinematics calculations. Unfortunately, the detection of the less energetic α_2 particles in the backward hemisphere is partially cut because of threshold effects. By measuring the yields of well identified α particles, we were able to reconstruct the angular distributions for the α_0, α_1 and α_2 channels leading respectively to the emission of a residual ^{12}C nucleus in the ground, first excited and Hoyle states. The agreement of shapes and of absolute values of the cross sections with the (sparse) data present in the literature are quite good [25, 26].

The angular distributions of the α_0 channel were then analyzed through a Legendre Polynomials decomposition, within the formalisms discussed in Refs. [27, 28]). The dominance of a particular even order of the B_i coefficients in a particular energy region will give information the ℓ_i, J^π and ℓ_f values for the excited states populated in that zone. As discussed in more details in a forthcoming article, even by considering the change of parity between the entrance and outgoing channels that complicated the analysis [28], it was possible to find clear signatures of the contribution of two resonant states, respectively at ≃ 24.1 and 24.5 MeV, with suggested J^π assignments being respectively 2^+ and 3^-. These findings were qualitatively confirmed by a similar analysis performed on the α_1 channel angular distributions, which is further complicated by the $S = 2$ channel spin in the outgoing channel.

In agreement with previous works (Refs. [26, 29, 30]), the data indicate the dominance of the compound nucleus (CN) reaction mechanism with respect to direct processes. The integrated cross sections for the ^{13}C(^{3}He,$\alpha_{0,1,2}$)^{12}C reactions here investigated are reported in Fig. 2 in different colors and symbols. The colored area indicated the experimental uncertainty of the α_2 channel due to the effects of identification thresholds on the reconstruction of angular distributions at backward angles.

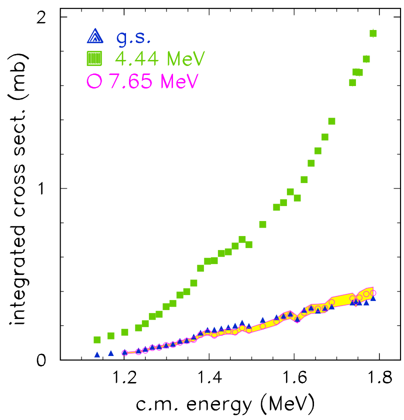

Figure 2. Integrated cross sections obtained for the ^{13}C(^{3}He,$\alpha_{0,1,2}$)^{12}C reactions, populating respectively the ^{12}C ground, 4.44, 7.65 MeV states. The gold colored area represents the uncertainty due to the partial reconstruction of the α particles emitted in the backward hemisphere.

From the integrated cross sections it is possible to estimate the Branching Ratio (BR) between two different decay channels; we performed such analysis especially on the α_2 to the α_0 channels, where the residual ^{12}C is respectively left in its Hoyle and ground state. The estimation of the BR is made simple by the fact that the two channels must have the same ℓ_{fin} from conservation laws. The branching ratio could be compared to the ratio of the penetrability of the α_2 and the α_0 decay channels, calculated through a simple barrier-penetration model and which shows an almost flat behavior, with no structure effects. In this frame, a region in which the $\frac{\alpha_2}{\alpha_0}$ BR is higher than the prediction given by the penetrability ratio will be linked to states having reduced widths $\gamma^2_{\alpha_2} > \gamma^2_{\alpha_0}$; this finding can give hints on the 4α cluster nature of the parent nucleus (^{16}O) states. Indeed, our data show two peaks at $E_x \approx 24.1$ and $E_x \approx 24.5$ MeV, corresponding to the previously observed states, well higher than the penetrability ratio calculations, suggesting their possible α-cluster nature. The implications of this finding in the cluster description of ^{16}O states at large excitation energies will be discussed in a forthcoming work.

4 Conclusions

High energy states in ^{16}O can be studied by means of ^{3}He + ^{13}C $\rightarrow$ ^{4}He + ^{12}C reactions performed at under-barrier energies. A new experiment of this type was performed at INFN-LNL, using the AN2000 accelerator and the OSCAR detector array. Very low threshold were needed to unambiguously identify each reaction channel involving the emission of α particles. The angular distributions of the α decay channels where ^{12}C was left in the ground state were analyzed with a Legendre polynomial decomposition, suggesting J^π assignments for two ^{16}O states in the $E_x = 24 - 25$ MeV region. Furthermore, a dedicated Branching Ratio analysis between the decay channels populating the Hoyle state or the ground state in the ^{12}C daughter nucleus evidenced the occurrence of unusually large values, possibly associated to the presence of clustered states at large excitation energies.

References

[1] C. Beck., *Lect. Not. Phys. 848* (Springer, 2010)
[2] M. Freer et al., Rev. Mod. Phys. **90**, 035004 (2018)
[3] I. Lombardo, D. Dell'Aquila, La Rivista del Nuovo Cimento pp. 1–98 (2023)
[4] I. Lombardo et al., J. Phys. Conf. Ser. **569**, 012068 (2014)
[5] J. Bishop et al., Phys. Rev. C **100**, 034320 (2019)
[6] L. Redigolo et al., J. Phys. G: Nucl. Part. Phys. **50**, 075101 (2023)
[7] L. Redigolo et al., J. Phys. G: Nucl. Part. Phys. **51**, 075106 (2024)
[8] D. Dell'Aquila et al., Scientific Reports **14**, 18958 (2024)
[9] L. Morelli et al., Physical Review C **99**, 054610 (2019)
[10] L. Redigolo, IL NUOVO CIMENTO **100**, 47 (2024)
[11] Y. Kanada-En'yo, D. Lee, Phys. Rev. C **103**, 024318 (2021)
[12] D. Tilley, H. Weller, C. Cheves, Nucl. Phys. A **564**, 1 (1993)
[13] W. Bauhoff, H. Schultheis, R. Schultheis, Phys. Rev. C **29**, 1046 (1984)
[14] F.I. R. Bijker, Phys. Rev. Lett. **112**, 152501 (2014)
[15] C. Halcrow, C. King, N.S. Manton, Phys. Rev. C **95**, 031303(R) (2017)
[16] N. Itagaki, A. Toshaki, Phys. Rev. C **97**, 014304 (2018)
[17] T. Fukui, Y. Kanada-En'yo, K. Ogata, T. Suhara, Y. Taniguchi, Nucl. Phys. A **983**, 38 (2019)
[18] K. Li, R. Neveling, P. Adsley, P. Papka, F. Smit et al., Phys. Rev. C **95**, 031302(R) (2017)
[19] M. Barbui, K. Hagel, J. Gauthier, S. Wuenschel, R. Wada et al., Phys. Rev. C **98**, 044601 (2018)
[20] S. Manna, T. Rana, C. Bhattacharya, S. Kundu, R. Pandey et al., Eur. Phys. J. A **57**, 286 (2021)
[21] A. Arima, V. Gillet, J. Ginocchio, Phys. Rev. Lett. **25**, 1043 (1970)
[22] M. Freer, N. Clarke, N. Curtis, B. Fulton, S. Hall et al., Phys. Rev. C **51**, 1682 (1995)
[23] R. Charity, K.W. Brown, J. Elson, W. Reviol, L. Sobotka et al., Phys. Rev. C **99**, 044304 (2019)
[24] D. Dell'Aquila et al., Nucl. Instr. Meth. Phys. Res. A **877**, 227 (2018)
[25] H.D. Holmgren, Phys. Rev. **106**, 100 (1957)
[26] K. Boehle, V. Meyer, H. Muller, Helv. Phys. Acta **44**, 367 (1971)
[27] J.M. Blatt, L.C. Biedenharn, Rev. Mod. Phys. **24**, 258 (1952)
[28] R.G. Sachs, *Nuclear Theory* (Addison-Wesley, 1953)
[29] V. Gomes-Porto, N. Ueta, R. Douglas, O. Sala, D. Wilmore et al., Nucl. Phys. A **136**, 385 (1969)

[30] H. Weller, N. Roberson, D. Tilley, Nucl. Phys. A **122**, 529 (1968)