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Clustering effects in nuclear reactions at low and medium energies

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Summary. — We discuss some recent achievements in the study of the structure of light and medium mass nuclei. In particular, we investigated the spectroscopy of ^{11}C and ^{12}C isotopes above the alpha emission threshold with low and medium energy nuclear reactions. The obtained results point out some interesting properties linked to possible cluster structure of such nuclei. Finally, we briefly discuss some investigations on possible effects linked to the cluster nature of the reaction partners in the low energy fusion of heavy ions.

1. – Introduction

Clustering phenomena represent a very old topic in nuclear physics (see, *e.g.*, [1]): they were invoked just at the beginning of nuclear structure studies to explain the occurrence of alpha decay from heavy nuclei. In a naive way, clustering could be seen as the grouping of nucleons into correlated sub-units, that play the role of fundamental constituents for the nuclear system. Clustering theories had a revival in the '30s, once noticed that the binding energies for self-conjugate nuclei (*i.e.*, nuclei with $N = Z$ and an even number of protons and neutrons, such as ^{8}Be, ^{12}C, ^{16}O and ^{20}Ne) were larger than the ones of neighbour nuclei. From that time, a strong evolution of both theoretical and experimental analyses has been observed, and the impact of clustering in other fields of nuclear physics (*e.g.*, in nuclear astrophysics [2, 3]) has been increasingly larger (see, *e.g.*, [4, 5]).

In addition to self-conjugate nuclei, also the case of isotopes away from the β-stability is particularly interesting: in analogy to physical chemistry, the presence of extra neutrons or protons may play a glue-like effect by stabilizing very deformed α-cluster structures by means of molecular-like bondings [6-8]. These considerations establish a close analogy with molecular chemistry, where the exchange of electrons allows the molecule binding. In nuclear neutron-rich systems, the wave-function of the valence neutrons can be spread out around α-particle cores, leading to the formation of π or σ orbitals [9-11].

The concept of nuclear molecular orbitals has been applied to beryllium, carbon and oxygen neutron-rich nuclei [8, 12-15], even if several questions are still open, especially in the analysis of the structure of carbon isotopes (*e.g.*, [9, 16, 17]). It is worth noting that a full understanding of such phenomena can be obtained only if the spectroscopy of light nuclei (as $^{13,14,15\ldots}$C, $^{17,18,19\ldots}$O, etc.) at energies close and above the alpha disintegration thresholds, is well known; unfortunately, for several isotopes, this is not the case, and new experimental analyses are often needed (see, *e.g.*, [18-20]).

Among the various nuclei characterized by a pronounced cluster structure, ^{12}C represents perhaps the most emblematic case (see, *e.g.*, [21]). In particular, the Hoyle state of ^{12}C, which plays a fundamental role in the triple alpha process in nuclear astrophysics, is the subject of a continuous research both on the theoretical and experimental sides (see, *e.g.*, [22, 23]). In particular, in the last years, we assisted to a rush towards the possible discovery of a non-vanishing direct decay branch into three alpha particles of the Hoyle state, that can have a large impact in some astrophysical domains (*e.g.*, white dwarfs) and can envisage also the formation of a Bose-Einstein condensate in a nuclear object [23, 24].

Nuclear clustering could also have an interesting impact on the dynamics of nuclear reactions between heavy ions. For example, the cluster structure of projectile and targets of a collision can facilitate the occurrence of incomplete momentum transfer phenomena at bombarding energies well above the barrier [25, 26]. In this respect, for example, the competition between complete and incomplete fusion of heavy ions could be influenced by the degree of clusterization of the reaction partners.

In this paper, we give an overview of some recent experimental investigations mainly focusing on the spectroscopy of carbon isotopes, with the aim of finding signatures of clusterization. We will treat in particular ^{11}C spectroscopy at large excitation energies as investigated by low energy nuclear reactions; then, we will give an overview of the decay properties of the Hoyle state, summarizing the results that we have obtained in the ^{14}N(d,α)^{12}C reaction, together with other recent investigations reported in the literature. Finally, I will briefly move to the heavy ion world, discussing the trend of the maxima in the complete fusion cross section and some possible interpretations about its origin.

2. – Spectroscopy of ^{11}C with the ^{10}B(p,α)^{7}Be reaction

The first isotope of carbon that we will discuss is the ^{11}C nucleus. It has a neutron less the self-conjugate ^{12}C nucleus, and it was pointed out that, at least at low excitation energies, its structure is strongly linked to the ^{11}B mirror nucleus [27]. On the theoretical side, both ^{11}C and ^{11}B nuclei were subject of interest because of the possible formation of cluster states, as discussed in ref. [28]. In particular, the $3/2^-_3$ state of ^{11}C, having an excitation energy of 8.10 MeV, seems to have a structure similar to the Hoyle state one, made by 2α-particles and a ^{3}He in loose interaction [28]. A similar structure was suggested also for the 8.56 MeV state in the mirror ^{11}B nucleus [27, 29]. Decays from the 8.65, 9.85, 10.7 and 12.1 MeV states in ^{11}C were clearly observed in ref. [30] and linked to the $K = 3/2^+$ and $K = 5/2^+$ rotational bands in ^{11}C. More recent investigations on the ^{11}B-^{11}C mirror couple were reported in ref. [31]; they underlined the potential presence of mirror states at large excitation energies (>10 MeV) and with high spins. The spectroscopy of ^{11}C states, obtained with R-matrix analysis of excitation functions of elastic scattering and reactions induced in $\alpha + {}^{7}$Be collisions, tentatively suggests the occurrence of rotational bands characterized by large moment of inertia, possibly linked to the formation of molecular-like structures. Anyway, uncertainties in spin-parity assignments and discrepancies with other works on the same reactions (*e.g.*, [32]) demand for new investigations.

In this framework, we studied the spectroscopy of ^{11}C by means of the ^{10}B(p,α)^{7}Be reaction, in the bombarding energy region 0.63–1.028 MeV. We coupled our data with existing elastic scattering ^{10}B(p,p)^{10}B cross sections already published in the literature [33]. In this way, it is possible to estimate partial widths of particle-unbound excited states in ^{11}C (see, *e.g.*, [31, 32, 34]), allowing us to derive information on their structure. It is interesting to emphasize that, as a by-product, the measurement of the absolute cross section of the ^{10}B(p,α)^{7}Be reaction can have a multi-disciplinary interest. In fact, in nuclear astrophysics, this reaction is the responsible for the disintegration of boron in hydrogen rich stellar environments [35]; it could also be an useful tool to constrain mixing phenomena occurring in such stars [36]. In applied physics research, a precise knowledge of the ^{10}B(p,α)^{7}Be cross section is important for the design and development of new-generation a-neutronic fusion reactors for the production of clean energy, as discussed in [37]. The ^{10}B(p,α) reaction at low energy can left the residual nucleus of ^{7}Be in its ground state (^{10}B(p,α_0)^{7}Be) or in its first excited state (^{10}B(p,α_1)^{7}Be, $E_x = 0.43$ MeV). Typically, at low energy (*e.g.*, $E_p < 1$ MeV), Coulomb barrier and phase space effects strongly hinder the α_1 channel compared to the α_0 one (see, *e.g.*, [38]). For this reason, in the present analysis we focus mainly on the α_0 channel, for which few and sparse data have been reported in the literature. In recent times, indirect methods such as the Trojan Horse Method (THM) [35, 39] have been used to investigate this reaction in the near and sub-barrier domain. In this energy region, the inclusive α_0 and α_1 cross-section has been measured by Jenkin *et al.* ($E_p \approx 3$–5.5 MeV) [40] and, more recently, by Kafkarkou *et al.* ($E_p \approx 2$–5.5 MeV) [41]. At lower bombarding energies ($E_p \approx 0.5$–2.0 MeV), very few data have been reported in the literature. The only existing angle-integrated measurement was performed with the activation technique, as reported in ref. [42]. Obviously, with this technique it is impossible to disentangle contributions due to α_0 and α_1 channels; furthermore, such data are affected by very large error bars, of the order of 20–30%. In the same energy region, very old data of ref. [43] ($E_p \approx 0.5$–1.6 MeV) and ref. [38] ($E_p \approx 0.8$–1.7 MeV) have been reported. They have been obtained with dedicated detection devices (a magnetic spectrometer and an electrostatic analyser, respectively). Unfortunately, both data sets deal with differential (and not integrated) cross-sections: [43] measured the differential cross section (DCS) for α_0 and α_1 channels obtained at $\theta_{cm} \approx 140°$, while angular distributions reported in ref. [38] involve just five bombarding energies, down to 1 MeV.

The present experiment was performed by using a proton beam delivered by the TTT3 tandem accelerator at the University of Naples "Federico II" [44-48]. The beam intensity was of the order of 1 nA, to minimize pile-up effects. The range here explored was $E_p = 0.63$–1.028 MeV in 40 keV step. The target was made by a boron foil (38 μg/cm^2 nominal thickness, isotopically enriched in ^{10}B at 99.9% level) with a small quantity of formvar ($C_3H_6O_2$, of the order some μg/cm^2) to reinforce it. A detailed analysis of contaminants present in the target show the presence of B, C, O (due to the boron foil and the formvar) and also of Cl, Cu, Ba (due to the copper mortar of the electron gun used to manufacture the boron foil and to the release agent, see ref. [48]). Due to kinematics, at backward angles we expect to see a strong overlap between the ejectiles of the ^{10}B(p,α_0) reaction and the ones of the ^{nat}Ba,Cu,Cl(p,p_0) scattering products. To overcome this problem, we used a novel subtraction technique (the *inverse absorber* method) discussed in details in ref. [48]. In this way, we succeed to extract the DCS of the ^{10}B(p,α_0)^{7}Be reaction from the experimental α_0 yields both in the forward and backward hemispheres. The absolute cross section scale was obtained with an internal normalization procedure, making use of the $p + {}^{10}$B elastic scattering yields and of the

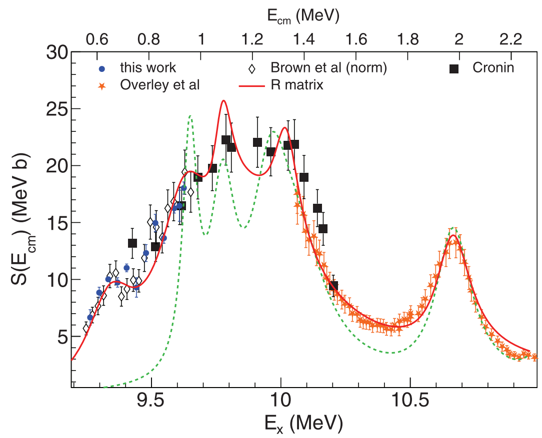

Fig. 1. – ^{10}B(p,α_0)^{7}Be astrophysical factor (blue points), compared to values obtained from the data sets reported in the literature [38,43,49]. Literature data have been integrated by assuming a nearly isotropic trend of cross sections.

data published in [33]. Our angular distribution at $E_p = 1.010\,\text{MeV}$ agrees well with the one reported by [38] at similar energy (1 MeV), testifying the consistency of the method here adopted. Angle-integrated cross sections of the ^{10}B(p,α_0)^{7}Be reaction are shown, in the form of astrophysical factor, in fig. 1 with full blue circles. The presence of a bump at ^{11}C excitation energy $E_x \approx 9.36\,\text{MeV}$ suggests the occurrence of a new ^{11}C excited state not reported in the literature. This finding is strongly supported by a comprehensive R-matrix fit of our data, coupled with other data reported in the literature and concerning other reaction [38, 43, 49] and scattering [33] channels. More details on the treatment of literature data here used are reported in [48]. The R-matrix analysis of data was made by using the R-matrix code AZURE2 [50, 51], using as a starting point of our fit procedure, the ^{11}C level scheme made by excited states at 8.699, 9.20, 9.65, 9.78, 9.97, 10.083, 10.67 MeV and the partial widths published in refs. [31, 32, 34, 52, 53]. The green dashed line in fig. 1 shows the result of the R-matrix by considering this initial set of parameters. A much better fit of data (red line) can be obtained by including a further state with J^π assignment $5/2^-$ at about the 9.36 MeV. The large α decay width of the 9.36 MeV state here found (about 70% of the corresponding Wigner limit) suggests the possible α-cluster nature of this state. After our investigations, other experiments have been performed on the ^{10}B(p,α_0)^{7}Be reaction at energies similar to the present ones, but using different techniques [54, 55]; both works consider the inclusion of a new state at around 9.36 MeV and with properties similar to the ones here reported. Finally, it is interesting to note that the energy position and spin-parity assignment of the 9.36 MeV state seem to fulfil well the occurrence of a negative parity band, built on the 8.104 MeV $3/2^-_3$ state, characterized by a large moment of inertia, and compatible with a $2\alpha+^3$He molecular-like structure (see, *e.g.*, [31]).

3. – Decay properties of the Hoyle state in ^{12}C

The second excited state of ^{12}C (7.654 MeV, 0^+) is very close to the 3α disintegration threshold ($\approx 7.275\,\text{MeV}$) and has a well pronounced cluster configuration. It plays a fundamental role in the triple-alpha process, as pointed out for the first time by Fred

Hoyle in the '50 [56]. Accurate investigations on its decay properties (concerning both charged particles and electromagnetic radiations) can be useful to derive information on its exotic structure [4,17] and can have a large impact in the determination of the reaction rate associated to the helium burning phase in stars (see, *e.g.*, [5,57]). It is interesting to note that, recently, some works [57, 58] reported radiative decay widths well larger than the values used in the literature for more than 40 years [59].

However, in this work we will focus our attention on the alpha decay of the Hoyle state. Two different decay modes are possible: sequential decay (SD) and direct decays (DD). Furthermore, DD can have different properties: they can be fully driven by the phase-space (DDΦ), can be linked to the presence of a linear chain (DDL), or they can lead to the emission of alpha particles with the same kinetic energy in the center of mass (*equal energy sharing*, DDE). Since the presence of DD, and notably of DDE, could be linked to the formation of a BEC in a nuclear system, it has been subject of several theoretical works and, subsequently, of an experimental rush toward a more stringent determination of the branching ratio of such elusive decay modes [5, 24, 60-64].

We contributed to clarify this question by performing a new experiment making use of a high-resolution hodoscope of silicon detectors [65], that is a modified version of the OSCAR telescope [66], made by with 64 $1 \times 1\,\mathrm{cm}^2$ individual silicon pads. An important advantage of this detector is the presence of independent detection units. In fact, previous works often made use of double-sided silicon strip detectors (DSSSD), and in such case the presence of misassigned tracks produced in DSSSDs can artificially enhance signals of DD, as discussed, *e.g.*, in ref. [63]. In our set-up, particle tracks are unambiguously reconstructed. To populate the Hoyle state, we used the ^{14}N(d,α)^{12}C reaction induced by a 10.5 MeV deuteron beam, produced at the Tandem accelerator at LNS, Catania. Alpha particles ejectiles related to the transition populating the Hoyle state were detected by an anti-coincidence telescope placed at backward angles ($\theta_{LAB} = 125°$). The hodoscope was placed at forward angles in kinematical coincidence with the expected recoils. Further details of the experimental set-up are discussed in [67]. The four-fold coincidence between the well identified alpha particle ejectile at backward angle and the three alpha particles coming from the decay of the Hoyle state allow a strong reduction of the background, and the good coverage assured by the hodoscope, with negligible distortions, of the kinematic decay cone, allowed us to disentangle the topology of different decay modes with a very limited number of background events [67]. Following ref. [63], we defined the so-called radial projection (ε_i) of the symmetric Dalitz plot built with the three alpha particles coming from the decay of the Hoyle state (see for example [5,67] and references therein). This is shown in fig. 2 with black stars. Results of Monte Carlo simulations assuming a 100% SD scenario are shown with a dashed line. It is evident that DD contributions, that can explore a region of the ε_i spectrum far from the main peak, are vanishingly small. By using the Feldman and Cousin's approach [68] for the analysis of small signals, we can estimate an upper limit on the branching ratio of the direct three α decay of 0.043% (95% C.L.). This value is about a factor 5 lower than the one found in the previous state-of-the-art experiment [63], and is in excellent agreement with a similar analysis performed in the same period by the Birmingham group with a different experimental technique [69].

In more recent times, new experiments performed with different techniques (*i.e.*, arrays of DSSSD and TPC) obtained upper limits similar or even smaller than the ones here discussed (see, *e.g.*, [70, 71]). All these findings triggered also new theoretical investigations, pointing out the important role of Coulomb and quantum effects in the triple alpha decay and the Hoyle state [72, 73].

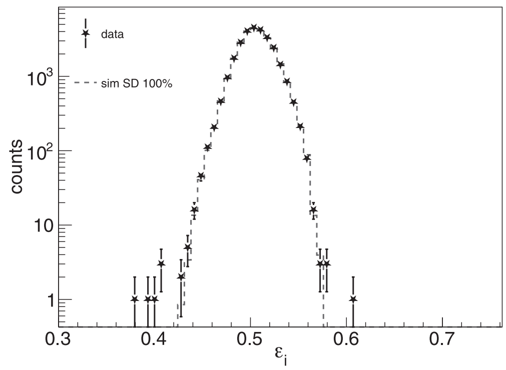

Fig. 2. – Radial projection (ε_i) of the symmetric Dalitz plot for the 3α decay of the Hoyle state in ^{12}C. More details can be found in ref. [67].

4. – Cluster effects in the limitation of complete fusion?

In the last section of this work, we will discuss on possible effects linked to the cluster structure of light nuclei on the evolution of reaction mechanisms in heavy ion collisions well above the Coulomb barrier. It is well known that, for collision systems of light to medium masses ($A_{tot} < 120$) and at bombarding energies larger than the Coulomb barrier, the complete fusion cross section is the dominant process, exhausting almost all the reaction cross section [74]. At increasingly large energies, however, the reaction cross section increases, while the complete fusion cross section σ_{cf} shows a maximum (σ_{cf}^{max}) and then a steep decrease [75, 76]. In the Fermi energy domain, complete fusion disappears in favour of more complex multi-fragmentation phenomena [77-79]. The origin of this effect is still debated: it could be due to peculiar properties in the entrance channel, or to limitation of the stability in the compound nucleus (CN). The relative velocities (corrected for the Coulomb barrier shift) where the maxima of the σ_{cf} occur (σ_{cf}^{max}) are, on the average, similar for many systems, $v_{rel} \approx 0.07c$ [80]. At similar values, ref. [25] reported the onset of incomplete fusion phenomena [81], well identified because of the incomplete momentum transfer between the reaction partners.

We performed a preliminary investigation involving the study of σ_{cf}^{max} as a function of CN and entrance channel properties. In the literature, it was already reported that σ_{cf}^{max} values oscillate depending on the studied system, but a clear determination of the nature of this trend is still missing; some suggested explanations, based mainly on effects related to the fusion Q-value, are discussed in refs. [82, 83]. In the present study, we extracted σ_{cf}^{max} values from a parabolic best fit of fusion data in the region of the maximum and we ordered them as a function of the total mass of the formed system A_{tot}, as shown in fig. 3. Two main effects can be seen: first, a weak increase of the σ_{cf}^{max} as a function of A_{tot}; second, a clear oscillatory trend of σ_{cf}^{max}, showing pronounced minima especially for systems made by a couple of self-conjugate nuclei. While the first point can be simply explained as a size effect, the second point could be related to effects due to nuclear structure in the balance between competitive reaction mechanism. We could naively imagine that self-conjugate nuclei should have a large tendency to break-up in clusters at large velocities, triggering in an easier way the occurrence of cluster transfer and incomplete fusion phenomena, thus reducing the probability of complete fusion. However, this simple picture does not take into account other important ingredients, as reduced

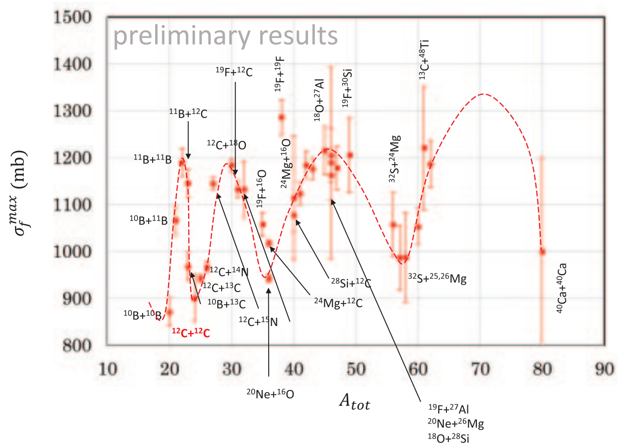

Fig. 3. – Trend of the maxima of complete fusion cross section for light systems as a function of the compound nucleus total mass. Arrows indicate the entrance channel of some selected systems.

mass, Coulomb barrier and Q-values of the fused system, that can influence fusion cross section. We are currently working on phenomenological models that can adequately take into account all these parameters in the description of the fusion excitation function above barrier, giving therefore the opportunity of evidencing effects that are instead related to nuclear structure.

5. – Summary

In this work, we reported some recent experimental results on the analysis of the cluster structure of excites states in ^{11}C and ^{12}C isotopes above the alpha emission threshold. We adopted two different techniques: the *R*-matrix analysis of excitation functions and angular distributions of low energy compound nucleus reactions for the ^{11}C case, and the study of multi-particle correlations for the analysis of decay mechanism in the Hoyle state in ^{12}C. Concerning ^{11}C, we found clear signals of the existence of a new state at 9.36 MeV, possibly having $J^\pi = 5/2^-$; the existence of this state was subsequently confirmed by other, independent, experiments. The alpha reduced width of this state is quite large, and it could belong to a molecular band built on a $2\alpha+^3$He cluster structure. Concerning the Hoyle state in ^{12}C, we investigated its triple alpha decay modes, and we found a complete dominance of the sequential decay mode through the ^{8}Be ground state; our results are in agreement with independent experiments performed on the same subject and stimulate new theoretical investigations to understand the fascinating nature of the Hoyle state. Finally, we performed a preliminary investigation on the trend of maxima in excitation functions of complete fusion events in heavy ion collisions. It seems that the oscillatory pattern seen in the data could be originated also by the cluster nature of the reaction partners in the entrance channels. We are currently performing further investigation on this topic. It is interesting to note that both particle-correlation experiments and absolute measurements of complete fusion cross sections discussed here could be profitably performed with high-segmentation and high-resolution detectors (*e.g.*, [79, 84-88]), using both stable and unstable beams.

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