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Opportunities of studying clustering in nuclei with the TTT3 tandem accelerator in Naples

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Summary. — The availability of a low-energy, high-resolution tandem accelerator in Naples triggered a series of experiments based on "classical" studies of nuclear spectroscopy with charged particles in low energy nuclear reactions. The accurate knowledge of spectroscopy of light nuclei allows to deduce important information on the structure of such systems and on the onset of alpha-clustering phenomena. Light self-conjugated (^{20}Ne) and non–self-conjugated (^{11,13}C) were the subjects of such experiments.

1. – Introduction

High precision studies of light nuclei have nowadays a prominent role in the field of nuclear physics. It is becoming in fact clearer and clearer that, if one wants to understand the details of effective nuclear forces by developing theoretical models, they must reproduce in the most accurate way all the peculiarities of such few-body systems [1]. Nuclear clustering is one of such peculiarities. It is associated with the presence of long range correlations in nuclear forces, and led to characteristic features in the so-called self-conjugated nuclei (^{8}Be, ^{12}C, ^{16}O, ^{20}Ne and so on) [2,3]. Signals of clustering have been reported also for neutron rich isotopes of light nuclei [4-6], and even for very heavy systems [7]. Theoretical models predict also an influence due to the formation of α clusters in the dynamics of heavy ion collisions (HIC) at low and medium energies [8]; in this respect, interesting signals can be found by studying the correlations between light charged particles and light fragments emitted in HIC [9-11], or even by studying the emission of fragments in collisions between self-conjugated medium mass nuclei [12,13].

The unveiling of clustering phenomena in nuclei often requires an accurate spectroscopic knowledge of all the excited states of light nuclei, in particular close to and above the N-α emission thresholds [1,4]. The largest part of the experimental investigations on such subjects were performed mainly during the 50–70 s, often with small detection devices having a limited energy resolution. In all cases, the lion's share in such experiment was played by high resolution electrostatic accelerators (often single-ended or tandem-van de Graaf types), able to deliver beams with excellent characteristics. Now that the technological development has led to the building of new detection devices with superior performance, we assist to a resurgence in the use of electrostatic accelerators with the aim of pushing at the limits our knowledge of the spectroscopy of light nuclear systems.

In this framework, an intense activity was recently carried out at the van de Graaf TTT3 tandem accelerator installed at the Dipartimento di Fisica "E. Pancini" of the Federico II University of Naples. This accelerator is operative in Naples since 1977, has been manufactured by the HVEC and is able to arrive up to 3.34 MV terminal voltage (the maximum was reached In March 2012; the nominal maximum terminal voltage of such machine was 3 MV). The TTT3 accelerator is coupled with two different ion sources: a radio-frequency source (used for producing ^{1,2}H, ^{3,4}He, ^{15}N beams) and a Kingston sputtering source (used to produce ^{1,2}H, ^{6,7}Li, ^{9}Be, ^{12,13}C, ^{16}O beams). The maximum measured ripple in the terminal voltage is about 50 V. Three multi-purpose reaction chambers and five channels for the beam transportation (also in air) are available, together with a dedicated FAIR-VME multi-parametric acquisition system. It was the first accelerator for radioactive beams (^{7}Be, in batch mode) operating in Italy.

In the following sections, I will give some sketch of the results obtained in several experimental campaigns performed at the TTT3 accelerator, with the aim of refining the knowledge on nuclear spectroscopy of ^{20}Ne and ^{11,13}C. The accelerator was also very useful for the testing of detection devices used for different types of experiments [14, 15].

2. – Study of ^{20}Ne via the ^{19}F(p,α_0)^{16}O reaction

Natural-parity states in ^{20}Ne at excitation energies larger than the proton emission threshold (12.844 MeV) are excited as resonances in the ^{19}F(p,α_0)^{16}O reaction at low energies [16]. We performed a new experimental investigation of the reaction cross section in the bombarding energy range 1.1–0.6 MeV in 20 keV steps, a region where very few (and conflicting) data sets in the literature prevented an accurate determination of the J^π of various states [16-18]. The α particles were detected with solid state detectors and were separated from the low-energy scattered protons by Al absorbers [19, 20]. The analysis of experimental angular distributions allowed to fix the J^π of the 13.642 MeV state (candidate to be a quartet state in ^{20}Ne) and to suggest the presence of a close-lying 1^- state at 13.632 MeV [19]. The experimental S-factor showed a low energy trend in agreement with the presence of broad resonances at very low energies [18, 21], and triggered a new experiment performed with a single-ended accelerator at LNL [22]. These experiments have significantly contributed in refining the current knowledge of the ^{19}F(p,α_0)^{16}O reaction rate in stars [23].

3. – Study of ^{11}C via the ^{10}B(p,α)^{7}Be reaction

^{11}C is a proton rich isotope of carbon, and several theoretical models predicted the appearance of $\alpha+\alpha+{}^{3}$He molecular structures at excitation energies near and above the $\alpha+{}^{7}$Be threshold [24]. Several spectroscopic uncertainties anyway limit a deeper understanding of such point [25]. In this framework, we performed in Naples a new measurement of the ^{10}B(p,α)^{7}Be reaction in a bombarding energy domain, E_p = 0.6–1.1 MeV, where no exclusive data points were reported in the literature, thus preventing the accurate knowledge of the spectroscopy of the compound nucleus, ^{11}C. Such a lack of data is mainly due to the difficulties in distinguishing the various ejectile emitted in elastic scattering on ^{10}B and in contaminants of the target. We overcame such problem by using the so-called *inverse absorber technique*, described in details in ref. [26]. Angular distributions and integrated cross section in absolute units were obtained, and the results were analyzed via a comprehensive R-matrix fit with the AZURE2 code [27]. Such analysis suggested the existence of a $5/2^-$ state at 9.36 MeV, characterized by γ_α^2 value close to the Wigner limit, and therefore candidate to be a cluster state of ^{11}C.

4. – Study of ^{13}C via the α+^{9}Be scattering

The spectroscopy of ^{13}C excited states at energies larger than alpha emission threshold can be fruitfully investigated by studying α+^{9}Be resonant elastic scattering at low energies [28], together with data from ^{9}Be(α,n)^{12}C reactions. A new experiment was performed with the TTT3 accelerator to obtain excitation functions in a broad energy domain ($E_\alpha \approx 3.6$–10 MeV) and at different polar angles in the backward hemisphere [29]. A dedicated thick target experiment was used to benchmark the absolute cross section scale obtained with the thin target experiment [30]. The experimental data so obtained, coupled with data from inelastic scattering and ^{9}Be$(\alpha, n)^{12}$C reactions, were simultaneously studied by an R-matrix analysis [27]. The obtained results are described in details in ref. [31] and allowed to improve the ^{13}C spectroscopy in the excitation energy range $E_x \approx 12$–18 MeV. Possible signals of the existence of a negative parity molecular band characterized by having a large moment of inertia were also seen, calling for further experimental efforts to deepen such aspect.

5. – Conclusions

In this proceeding I discuss the opportunity given by the availability of low-energy, high-resolution electrostatic accelerators for making nuclear spectroscopy investigations. In particular, I briefly summarized the results obtained with the TTT3 tandem accelerator in Naples in the improvement of spectroscopy of ^{20}Ne and ^{11,13}C with the aim of unveiling the appearance of clustering phenomena in such nuclei.

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