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A full-comprehensive experimental and theoretical approach applied to the ^{12}C(^{18}O,^{18}F)^{12}B single charge-exchange reaction at 15.3 AMeV

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Summary. — The broad network of nuclear reactions coming from the ^{18}O + ^{12}C collision was studied to test the capability of state-of-art nuclear structure and reaction theories in describing the ^{12}C(^{18}O,^{18}F)^{12}B single charge-exchange reaction using a new comprehensive experimental and theoretical multi-channel approach. The experiment, performed in Catania, at the Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare (LNS-INFN), used the ^{18}O beam at 15.3 AMeV incident energy produced by the K800 Superconducting Cyclotron and the MAGNEX magnetic spectrometer.

1. – Introduction

The study of heavy-ion direct nuclear reactions induced by the ^{18}O beam at 15.3 AMeV incident energy on the ^{12}C target performed at the INFN-Laboratori Nazionali del Sud (INFN-LNS) is the main topic of the research presented in this paper. This work is devoted to shed light on heavy-ion induced reaction mechanisms, especially for the single and double charge-exchange nuclear reactions. The scientific background and motivation come from the NUMEN [1, 2] (NUclear Matrix Elements for Neutrino-less double-beta decay) project, aiming at studying heavy-ion nuclear reactions in order to extract information on the Nuclear Matrix Elements (NMEs) of interest in the context of neutrino-less double beta ($0\nu\beta\beta$) decay research [3, 4]. The $0\nu\beta\beta$-decay is considered to be the *experimentum crucis* to reveal the Majorana nature of neutrinos and the lepton-number violation. It is a link between the current and next-generation physics beyond the standard model [5].

The main feature and novelty of the method consist in the application of a new *holistic* approach. Indeed, the high level of complexity of the single and double charge-exchange

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Table I. – *Target thickness, range of scattering angles* $[\theta_{lab}^{min};\theta_{lab}^{max}]$*, central angle* θ_{opt} *and solid angle of the MAGNEX magnetic spectrometer for each of the reaction channels studied during the* $^{18}O + ^{12}C$ *experimental campaign at 15.3 AMeV incident energy.*

		Target thickness (μg/cm^2)	$[\theta_{lab}^{min};\theta_{lab}^{max}]$ (deg)	θ_{opt} (deg)	Solid angle (msr)
el. & inel.	^{12}C(^{18}O,^{18}O)^{12}C	60 ± 3 400 ± 20 60 ± 3	[3.5; 14.2]	7.5 9.0 13.5	49.2 13.6 49.2
1n-transfer	^{12}C(^{18}O,^{17}O)^{13}C	200 ± 10 60 ± 3	[3.1; 17.5]	8.0 13.5	13.6 49.2
2n-transfer	^{12}C(^{18}O,^{16}O)^{14}C	60 ± 3 60 ± 3	[3.0; 19.0]	7.5 13.5	49.2 49.2
1p-transfer	^{12}C(^{18}O,^{19}F)^{11}B	60 ± 3 200 ± 10 60 ± 3	[3.6; 16.1]	7.5 8.0 13.5	49.2 13.6 49.2
SCE	^{12}C(^{18}O,^{18}F)^{12}B	60 ± 3 200 ± 10 60 ± 3	[3.2; 14.3]	7.5 8.0 13.5	49.2 13.6 49.2

reaction mechanisms implies the involvement of several nuclear properties arising from the many-body nature of the nuclei candidate to the $0\nu\beta\beta$-decay. In the present case, the method is applied to the analysis of the ^{18}O + ^{12}C system that has been selected as an ideal benchmark to test the newly developed method for two main reasons. Firstly, the low level density of the nuclei involved in the reaction network allows isolating transitions towards single states. Moreover, all the nuclear features have been extensively debated in the literature [6].

The study of the ^{12}C(^{18}O,^{18}O)^{12}C elastic and inelastic scattering allows accessing the initial state interaction (ISI) responsible for the distortion of the many-body wave functions of the incoming ^{12}C and ^{18}O nuclei, relevant to properly describe all the reaction channels. The ^{12}C(^{18}O,^{16}O)^{14}C two-neutron transfer reaction analysis, whose results have been recently published in ref. [7], confirmed the observation of the giant pairing vibration (GPV) observed for the first time in ref. [8]. The ^{12}C(^{18}O,^{19}F)^{11}B one-proton knock-out and the ^{12}C(^{18}O,^{17}O)^{13}C one-neutron pick-up nuclear reactions are designated to constrain the single particle components of the many-body nuclear wave functions of the involved nuclei. Finally, an interesting aspect of the ^{12}C(^{18}O,^{18}F)^{12}B single charge exchange (SCE) nuclear reaction study regards the competition between the direct process, proceeding via the meson-exchange reaction mechanism, and the neutron-proton and/or proton-neutron sequential-transfer processes [4].

2. – Methods and preliminary results

The experiment was performed using the ^{18}O^{4+} ion beam accelerated by the INFN-LNS K800 Superconducting Cyclotron at 15.3 AMeV bombarding energy. Thin ^{nat}C foils were used as targets in the different experimental runs. The beam current at the target

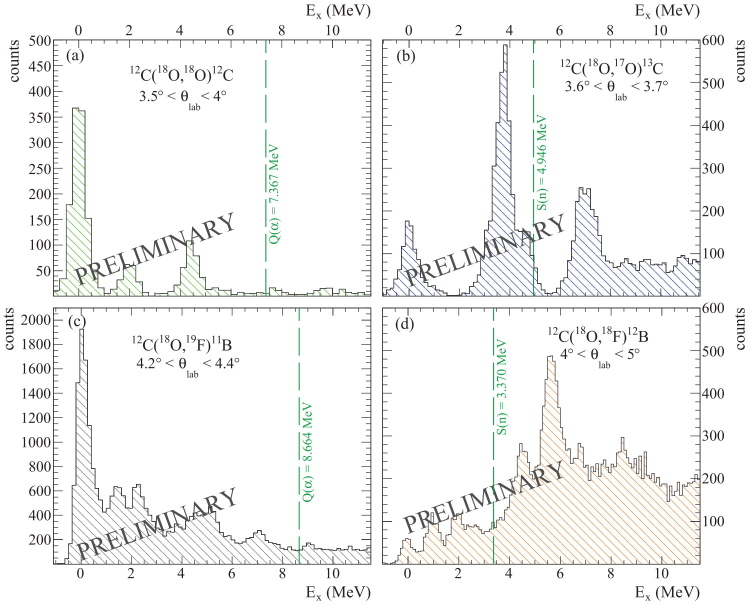

Fig. 1. – Preliminary excitation energy spectra for some of the nuclear reactions involved in the multi-channel study presented in this work at 15.3 AMeV incident energy: (a) ^{12}C(^{18}O,^{18}O)^{12}C elastic and inelastic scattering. (b) ^{12}C(^{18}O,^{17}O)^{13}C one-neutron pick-up. (c) ^{12}C(^{18}O,^{19}F)^{11}B one-proton knock-out. (d) ^{12}C(^{18}O,^{18}F)^{12}Be single charge exchange. Covered angular ranges, neutron separation energy $S(n)$ and the alpha Q-value $Q(\alpha)$ are indicated in the figures.

was measured by a Faraday cup located, along the beam direction, 15 cm downstream from the target. The particle identification and the analysis of the momenta of the ejectiles emerging from the nuclear reactions was performed thanks to the MAGNEX magnetic spectrometer [9]. The spectrometer optical axis was set at different scattering angles in each experimental run and a specific configuration of the angular acceptance was adopted by setting movable horizontal and vertical slits located at the entrance of the spectrometer. Target thicknesses, covered scattering angles, spectrometer optical angles and covered solid angles are listed in table I for each of the analysed reaction channels. The magnetic fields of the dipole and quadrupole magnets were set in order to transport the ^{18}F^{9+}, ^{19}F^{9+}, ^{17}O^{8+} and ^{16}O^{8+} ions, corresponding to the ejectiles of the nuclear reactions of interest, in the region of momenta covered by the MAGNEX focal plane detector (FPD) [10]. The elastic and inelastic scattering was performed in a different magnetic set, since the magnetic rigidity of the ^{18}O^{8+} differed quite significantly from those of the other ions.

The data reduction strategy, applied to each of the reaction channels, has been extensively described in previous publications and reviewed in ref. [9]. The procedure includes the vertical and horizontal position calibration of the track-ions at the FPD, identification of the ejectiles and reconstruction of the momentum vector at the target by inverting the transport equations [11]. The accurate set-up and the advanced data reduction have allowed producing high resolution energy spectra and angular distributions for the all the analysed channels. The excitation energy E_x was calculated as the difference $Q_0 - Q$ where the Q_0 is the ground-to-ground state Q-value and Q is the Q-value obtained by the missing mass technique based on relativistic kinematic transformations. Preliminary examples of the elastic and inelastic scattering, one-proton knock-out, one-neutron pick-up and SCE nuclear reaction excitation energy spectra are shown in fig. 1. The energy resolution is about 0.6 MeV, slightly dependent on the reaction channel due to the different energy straggling produced by the ejectile/target interaction. The achieved energy resolution was enough to single out transitions to isolated or grouped states of the final nuclei. Absolute cross-section angular distributions were extracted for the several structures clearly visible in the spectra. Theoretical analysis is in progress and will be presented in a forthcoming paper.

3. – Summary and perspectives

A new multi-channel approach to the study of heavy-ion induced nuclear reactions, proposed by the NUMEN project, has been presented in this paper. Preliminary results for the measured energy spectra of different reaction channels populated in the $^{18}\mathrm{O}+{}^{12}\mathrm{C}$ collision at 15.3 AMeV are shown. The choice of projectile and target was driven by the availability of accurate information on the involved low-lying states in this mass region from experimental results and nuclear structure models. Thus the $^{18}\mathrm{O}+{}^{12}\mathrm{C}$ system is an ideal benchmark to test the proposed multi-channel constrained technique.

The sequential nucleon-transfer and the direct meson-exchange are expected to play a comparable role in the full $^{12}\mathrm{C}(^{18}\mathrm{O},^{18}\mathrm{F})^{12}\mathrm{B}$ SCE reaction mechanism at 15.3 AMeV incident energy, as stated by the authors of refs. [12] and [13] in the case of the $^{12}\mathrm{C}(^{7}\mathrm{Li},^{7}\mathrm{Be})^{12}\mathrm{B}$ and $^{12}\mathrm{C}(^{12}\mathrm{C},^{12}\mathrm{N})^{12}\mathrm{B}$ reactions, respectively. The description of the measured cross-sections will require the non trivial coherent sum of these two components. To do that, the nuclear structure and reaction ingredients involved in the building of the meson-exchange and nucleon-transfer reaction form factors, such as the spectroscopic amplitudes, transition densities and the radial shapes of the single particle wave-functions, need to be extracted in the framework of the same models. The development of new tools to manage and control all these aspects, historically treated in different theoretical frameworks, is still in progress and constitutes the main perspective of the present study.

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