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The multichannel experimental and theoretical study of the ^{12}C(^{18}O,^{18}F)^{12}B single charge exchange reaction mechanism

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Abstract. The study of a network of nuclear reactions populated in the ^{18}O + ^{12}C collision is the main topic of the present paper. It was performed to test nuclear structure and reaction theories in describing the full reaction mechanism occurring in the (^{18}O, ^{18}F) single charge exchange nuclear reaction. From the experimental side, an ^{18}O beam was produced at 275 MeV incident energy by

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the K800 superconducting cyclotron and the MAGNEX magnetic spectrometer was used at the Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare to momentum analyse the ejectiles produced in the nuclear reactions within the same experimental setup. From the theoretical side, the proposed approach consists of analysing the whole network of nuclear reactions in the framework of a unique comprehensive and coherent theoretical calculation. This holistic approach, applied both to the experimental and theoretical analysis, is the main feature and novelty of the work presented here.

1 Introduction

The study of heavy-ion direct nuclear reactions induced by the ^{18}O beam at 15.3 AMeV incident energy on a ^{12}C target, performed at the INFN-Laboratori Nazionali del Sud (INFN-LNS), is the topic of the present 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 motivation comes from the purposes of the NUMEN [1, 2] (NUclear Matrix Elements for Neutrino-less double-beta decay) project, aiming at studying heavy-ion nuclear reactions 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. 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 and is a link between the current and next-generation physics beyond the standard model [3].

The spread in the results of about a factor of three for the $0\nu\beta\beta$ NMEs, calculated among different nuclear structure theories, needs to be overcome if we wish to fully exploit an eventual measurement of the decay half-life [4]. The NUMEN project suggests the possibility to constrain the NMEs' calculations using a new data-driven approach consisting of the study of double charge-exchange (DCE) nuclear reaction cross-sections[5, 6], particularly relevant for the $0\nu\beta\beta$ decay physics since the NMEs for DCE and $0\nu\beta\beta$ decay transitions share the same initial and final nuclear states [1].

The capability of state-of-the-art nuclear theories to give the clearest and the most complete description of the DCE reaction mechanism is a crucial point to extract the nuclear structure information relevant for the $0\nu\beta\beta$ NMEs. Indeed, the complete DCE reaction mechanism is a competition of three possible contributions [7]: *i)* the direct process, called Majorana DCE [8], in analogy to the direct $0\nu\beta\beta$ Majorana process; *ii)* the double Single Charge-Exchange (double-SCE) process, consisting of two direct-SCE steps, in analogy to the $2\nu\beta\beta$-decay [9]; *iii)* the multi-nucleon transfer process involving all the possible one- and two-nucleon successive transfers connecting the same initial and final DCE partitions. Recent studies are excluding a relevant role of the multi-nucleon transfers in the DCE reaction mechanism [10, 11], whereas the role of the double-SCE is to date far from being considered negligible. In that case the double-SCE contribution to the total DCE can be estimated considering a folding of two SCE reaction amplitudes [9].

The main novelty of the present work consists of the application of a new multichannel approach. Indeed, the high level of complexity of the single and double charge-exchange 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 study of the ^{18}O + ^{12}C system at 275 MeV incident energy. Although they are not $\beta\beta$-decay candidates, the choice of such projectile and target was driven by the available accurate information on the involved low-lying nuclear states in this mass region from experimental results and large scale shell-model calculations, making this system an ideal benchmark for the proposed multichannel constrained technique. The new multichannel experimental and theoretical approach, once tested, can be further applied to the study of the $\beta\beta$-decay candidates.

The first results of this study were recently published in Ref. [12]. These results include the study of the $^{12}C(^{18}O,^{18}O)^{12}C$ elastic and inelastic scattering allowing to access the initial-state interaction (ISI) responsible for the distortion of the many-body wave functions of the incoming ^{12}C and ^{18}O nuclei; the $^{12}C(^{18}O,^{19}F)^{11}B$ one-proton stripping and the $^{12}C(^{18}O,^{17}O)^{13}C$ one-neutron pick-up nuclear reactions, designated to constrain the single particle components of the many-body nuclear wave functions of the involved nuclei. Moreover, the $^{12}C(^{18}O,^{16}O)^{14}C$ two-neutron transfer reaction analysis, whose results have been recently published in Ref. [13], confirmed the observation of the giant pairing vibration (GPV) observed for the first time in Ref. [14]. 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 [8]. This study is still in progress and will be presented in the forthcoming publications.

2 Methods and results

The experiment was performed at INFN-LNS [15] where the ^{18}O beam was accelerated up to 275 MeV by the K800 Superconducting Cyclotron. The 60 ± 3 $\mu g/cm^2$ and the 200 ± 10 $\mu g/cm^2$ thick ^{nat}C self-supporting targets were located in the object point of the MAGNEX magnetic spectrometer [16]. A Faraday cup and an electron suppressor were used to stop the beam and collect the charge with a collection accuracy better than 10% in all the experimental runs. The MAGNEX optical axis was oriented, compared to the beam direction, at θ_{opt} = 7.5°, 8° and 13.5°. 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) [17]. The study of the elastic and inelastic scattering was performed in a different magnetic set since the magnetic rigidity of the $^{18}O^{8+}$ is too different with respect to the ones of the other ions to be detected in the same magnetic set. The data reduction strategy includes the position calibration of the FPD, identification of the ejectiles and reconstruction of the momentum vector at the target by inversion of the transport equations following the guidelines presented in previous publications [18, 19].

The elastic and inelastic scattering, one-proton stripping, one-neutron pick-up and SCE nuclear reaction excitation energy spectra were previously published in Refs. [12, 20, 21]. An example from Ref. [12] is shown in Fig. 1. 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. The energy resolution (≈ 0.6 MeV) is 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 residual nuclei. Absolute cross-section angular distributions were extracted for the several structures clearly visible in the spectra. Theoretical analysis for the elastic and inelastic scattering, one-proton stripping, one-neutron pick-up are published in Ref. [12] while the complete analysis of the SCE reaction channel mechanism will be published in forthcoming publications.

An important ingredient to study the direct nuclear reactions is the initial-state interaction (ISI), including the optical and the coupling potentials to the relevant states of the elastic/inelastic partition. In the case of these reaction channels, calculations were performed within the optical model (OM), coupled channels (CC), and coupled reaction chan-

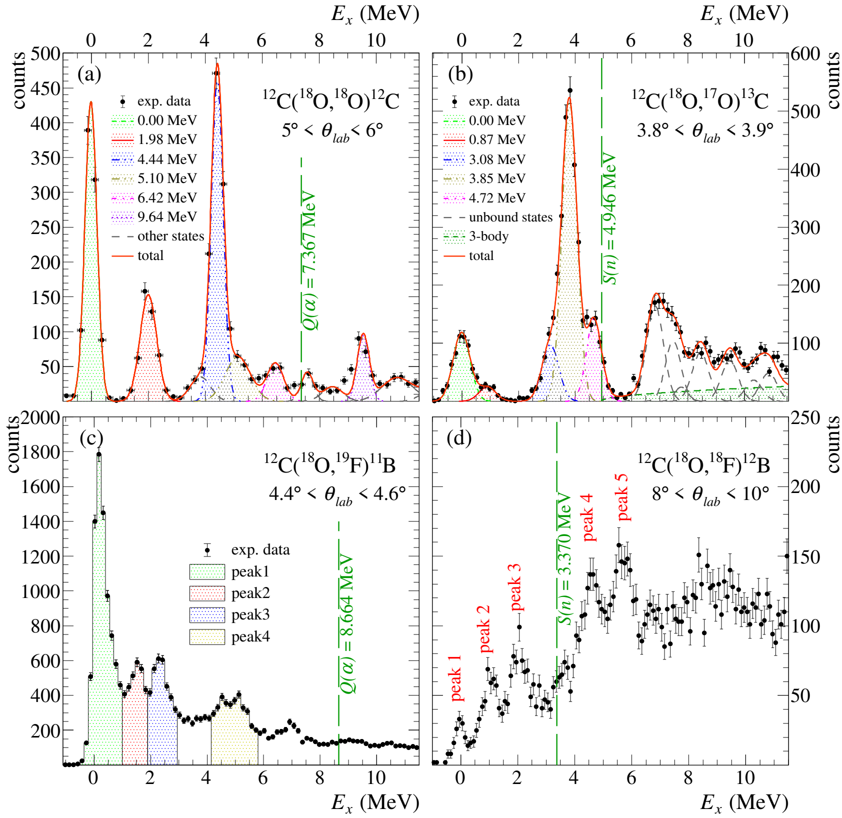

Figure 1. Excitation energy spectra for the net of nuclear reactions involved in the multichannel study of the single charge exchange reactions coming from the ^{18}O + ^{12}C collision at 275 MeV incident energy. (**a**) ^{12}C(^{18}O,^{18}O)^{12}C elastic and inelastic scattering energy spectrum at 5° < θ_{lab} < 6°. Lines, obtained from best-fit procedure, identify peaks corresponding to the superposition of the projectile and target states, as labeled in the legend. (**b**) ^{12}C(^{18}O,^{17}O)^{13}C one-neutron stripping energy spectrum at 3.8° < θ_{lab} < 3.9°. Lines, obtained from best-fit procedure, identify peaks corresponding to the superposition of the projectile and target states, as labeled in the legend. (**c**) ^{12}C(^{18}O,^{19}F)^{11}B one-proton pick-up energy spectrum at 4.4° < θ_{lab} < 4.6°. The hatched areas indicate the regions of interest for the study of the angular distributions as labeled in the legend. (**d**) ^{12}C(^{18}O,^{18}F)^{12}Be single charge exchange energy spectrum at 8° < θ_{lab} < 10°. Figure from Ref. [12].

nels (CRC) methods. Regarding the optical potential, the analysis was performed using the São Paulo potential (SPP) [22] $V_{SPP}(r)$ as the real and the imaginary parts of the OP $U(r) = (N_R + iN_I)V_{SPP}(r)$, where N_R and N_I are the real and imaginary strength factors, respectively. Although the N_R value is always set to 1, N_I is changed according to the coupling scheme adopted in the reaction calculations. Indeed, the imaginary part is introduced to account effectively for the absorption to reaction channels and inelastic transitions, not explicitly introduced in the coupling scheme. In OM, where the only included channel in the coupling scheme is the elastic one, N_I is typically set to 0.78 [23]. If the couplings with the strongly populated inelastic scattering channels is explicitly taken into account, as in CC, and CRC approaches, the N_I value is typically reduced to 0.6 [24]. The $V_{SPP}(r)$ [22] comes from

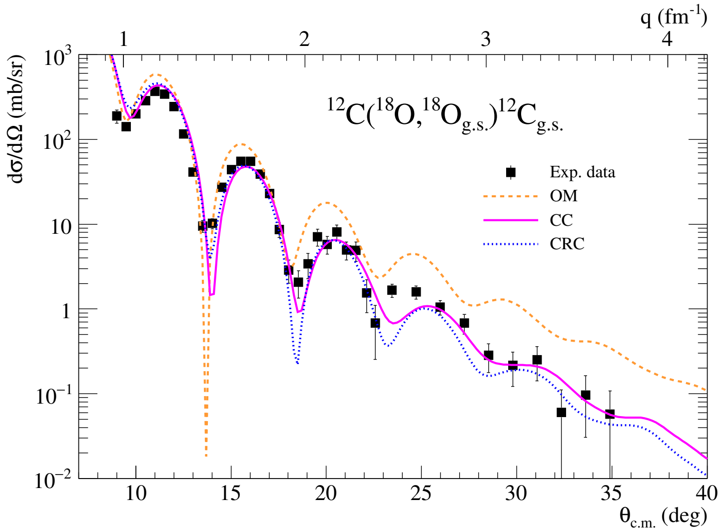

Figure 2. Experimental cross-section angular distribution of the ^{12}C(^{18}O,^{18}O)^{12}C elastic scattering at 275 MeV incident energy. Theoretical calculations for the elastic transition in OM, CC and CRC approaches are shown with the orange dashed, solid magenta and blue dotted lines, respectively.

the double folding of a finite-range folding-type effective nucleon-nucleon interaction with the matter densities of the heavy nuclei involved in the collision.

The results of OM, CC and CRC calculations for the ^{18}O + ^{12}C elastic scattering at 275 MeV incident energy are shown in Fig. 2. The Fraunhofer diffraction pattern (Sommerfeld parameter $\eta = 1.9$) is clearly visible in both experimental and theoretical angular distributions and a good agreement is present for transferred momenta up to $q \approx 2$ fm^{-1}. The discrepancy observed at larger q suggests the need to explicitly include the couplings with the first low-lying inelastic transitions, as already observed in similar studies [25–31]. This task is accomplished assuming a collective or a microscopic model with the proper coupling potentials [12].

3 Summary and Perspectives

A new multichannel 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}O + ^{12}C collision at 275 MeV, 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}O+^{12}C system is an ideal benchmark to test the proposed multichannel constrained technique.

The experimental and theoretical study of the ^{12}C(^{18}O,^{18}O)^{12}C elastic and inelastic scattering was performed to access the initial-state interaction (ISI) responsible for the distortion of the many-body wave functions of the incoming nuclei. The role of the ISI is crucial to properly describe all the direct nuclear reaction channels. In addition to the role of the ISI and the many-body properties of the nuclear wave functions involved in the studied reactions, the most crucial and debated aspect in the study of the SCE nuclear reactions is the competition between the direct process, proceeding via the deeply studied meson-exchange [8] and the sequential neutron-proton or proton-neutron transfer processes. 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 theories. The development of new tools to manage and control all these aspects, historically treated in different theoretical frameworks, is in progress and constitutes the main perspective of the present study.

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