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Multi-channel experimental and theoretical approach to study the ^{12}C(^{18}O,^{18}F)^{12}B single charge exchange reaction

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Abstract. The broad network of nuclear reactions populated in the ^{18}O + ^{12}C collision was studied to test the capability of state-of-art nuclear structure and reaction theories to describe both the direct and sequential components of the (^{18}O, ^{18}F) single charge exchange nuclear reaction. The experiment was performed using the ^{18}O beam at 275 MeV incident energy produced by the K800 superconducting cyclotron and the MAGNEX magnetic spectrometer at the Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare. A unique comprehensive and coherent theoretical calculation, able to describe the whole network of direct reactions, is the approach proposed for the first time to analyse this large set of experimental data. This holistic approach, applied both to the experimental and theoretical analysis, is the main feature and novelty of the work here presented.

1. Introduction and motivation

The scientific background and motivation of the presented work is common to that of the NUMEN [1] (Nuclear Matrix Elements for neutrino-less double-beta decay) project aiming to extract information about the Nuclear Matrix Elements (NMEs) of interest in the context of neutrino-less double beta decay ($0\nu\beta\beta$) research. This process is considered the *experimentum crucis* to reveal the Majorana nature of neutrinos and the lepton-number violation, being a link between the current and next-generation physics beyond the standard model [2]. The role of nuclear matrix elements (NMEs) in $0\nu\beta\beta$ research is crucial to design the next-generation experiments and to access the neutrino effective mass, if the process will be actually observed [3].

The spread in the results of about a factor of three for the NMEs calculated among different nuclear structure theories need to be overcome since reducing the uncertainty in the matrix element calculations will be crucial 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. It consists in the study of double charge-exchange (DCE) nuclear reaction cross-sections, 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]. Recently, the linear correlation between the DCE double Gamow-Teller (DGT) NMEs and the $0\nu\beta\beta$ DGT and total NMEs was demonstrated using both the interacting-boson model and the large-scale shell-model nuclear structure approaches [5, 6]. Promising results regarding the possibility to extract the DCE NME from the experimental cross-section measurements have been achieved in the last few years [7, 8, 9].

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. The complete DCE reaction mechanism is a competition of three possible contributions [7]: *i)* the direct process, called Majorana DCE [10], 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; *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 [11, 12], 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 theoretical ingredients required to perform this study are both from nuclear structure and reaction physics. The response of nuclei to the first- and second-order isospin and spin-isospin operators, and the single-particle or correlation features coming from the mean-field or residual interaction, respectively, are the relevant nuclear structure information. On the other side, the introduction of an average interacting potential to describe the relative motion of the colliding nuclei, the proper description of the residual interaction and the dynamical effects responsible to couple states of the same or different partitions, are the main nuclear reaction theory aspects needed to be addressed. From the experimental side, a good understanding of such properties implies the necessity to study a wide network of nuclear reactions including the elastic and inelastic scattering, the one and two-nucleon transfer, the SCE and DCE nuclear reactions. Furthermore, the NUMEN project wants to study the (^{18}O,^{18}Ne) DCE reaction as a probe for the $\beta^+\beta^+$ transitions and the (^{20}Ne,^{20}O) one for the $\beta^-\beta^-$, with the aim to explore the DCE mechanism in both directions [1]. Since NMEs are *time invariant* quantities, they are common to a DCE and to its inverse, so the contextual measurements of both directions in the DCE represent a useful test of the procedure to extract NME from the measured DCE cross-section.

The main feature and novelty of the work presented at the conference concern both experimental and theoretical aspects. From the experimental side, the idea is to produce new data of the angular distributions and energy spectra differential cross-sections measured in the same experiment for a broad network of nuclear reactions. From the theoretical side, the purpose is to analyse the experimental data using state-of-the-art nuclear structure and reaction theories in a unique full-comprehensive and coherent calculation. This approach has been applied to the study of many nuclear reaction channels involving 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 nuclear low-lying states in this mass region from experimental results and large scale shell-model calculations, making this system an ideal benchmark for the proposed multi-channel constrained technique. The new multi-channel experimental and theoretical approach, once tested, can be further applied to the study of the $\beta\beta$-decay candidates.

2. Methods and preliminary results

The ^{18}O beam was accelerated up to 275 MeV by the K800 Superconducting Cyclotron of INFN-LNS. The ^{18}O ions impinged on the thin targets located in the object point of the MAGNEX magnetic spectrometer [13], inside its scattering chamber. The 60 ± 3 μg/cm^2 and the 200 ± 10 μg/cm^2 thick $^{\mathrm{nat}}$C self-supporting targets have been used during the measurements. A Faraday cup of 0.8 cm entrance diameter and 3 cm depth, mounted 15 cm downstream of the target, was used to stop the beam and collect the charge. An electron suppressor polarized at -200 V and a low noise charge integrator allowed to keep the charge collection accuracy better than 10% in all the experiment runs.

The ejectiles, produced in the reactions were momentum analysed in different runs in which the optical axis of MAGNEX was oriented, compared to the beam direction, at $\theta_{opt} = 7.5°$, 8° and 13.5°. The MAGNEX entrance solid angle was set in the full acceptance configuration ($\simeq$ 50 msr) or it was reduced in the vertical dimension to $\simeq$ 14 msr by means of slits located at the entrance of the spectrometer. The beam current was optimized at each optical angle configuration in order to reach event rates tolerable by the focal plane detector (FPD) [14]. 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 FPD. The study of the elastic and inelastic scattering was performed in a different magnetic set because of 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 [15].

The accurate set-up and the advanced data reduction have allowed to produce high resolution

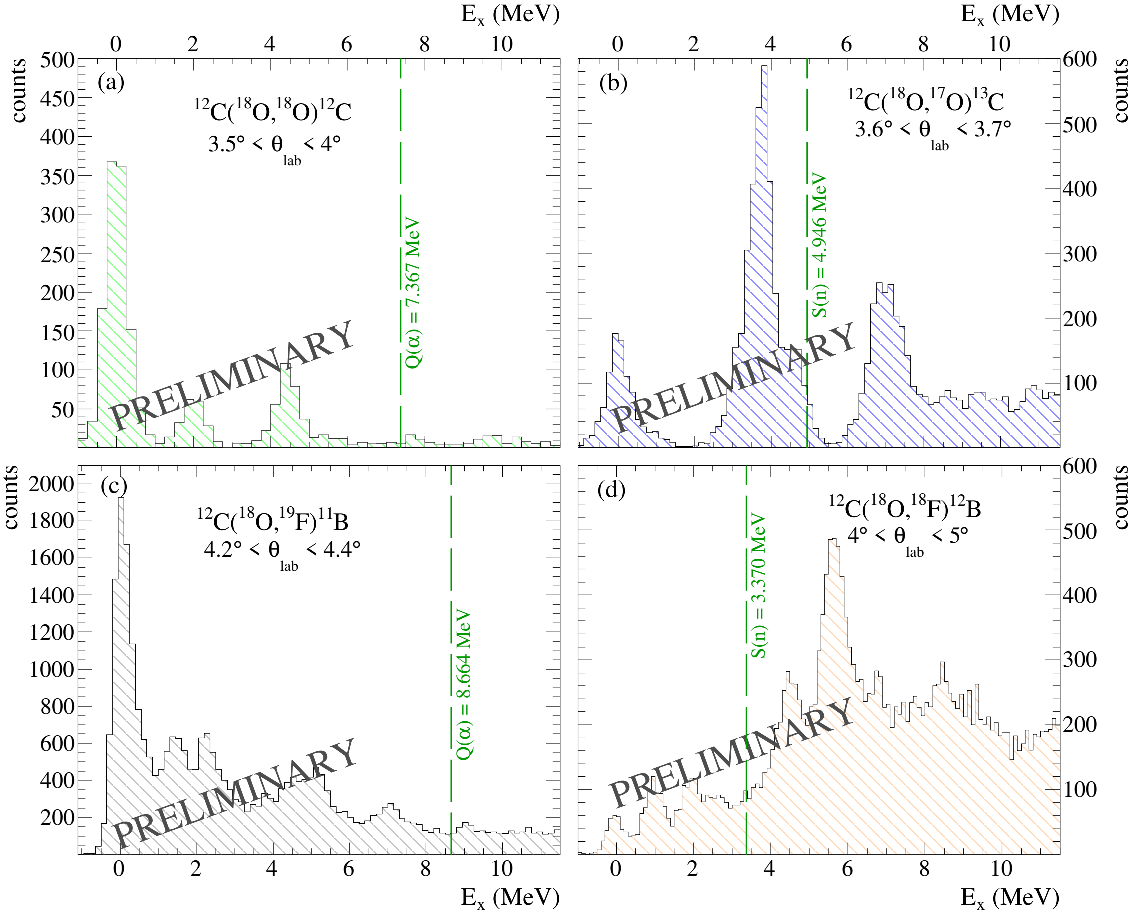

Figure 1. Preliminary excitation energy spectra for nuclear reactions involved in the multi-channel study presented in this work at 275 MeV incident energy: (**a**) ^{12}C(^{18}O,^{18}O)^{12}C elastic and inelastic scattering. (**b**) ^{12}C(^{18}O,^{17}O)^{13}C one-neutron stripping. (**c**) ^{12}C(^{18}O,^{19}F)^{11}B one-proton pick-up. (**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(α) are also indicated. Figure from Ref. [16].

energy spectra and angular distributions for 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 have been previously shown in Ref. [16] and are reported 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 forthcoming papers.

An important 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 [10] and the sequential neutron-proton or proton-neutron transfer processes [17]. The three main paths

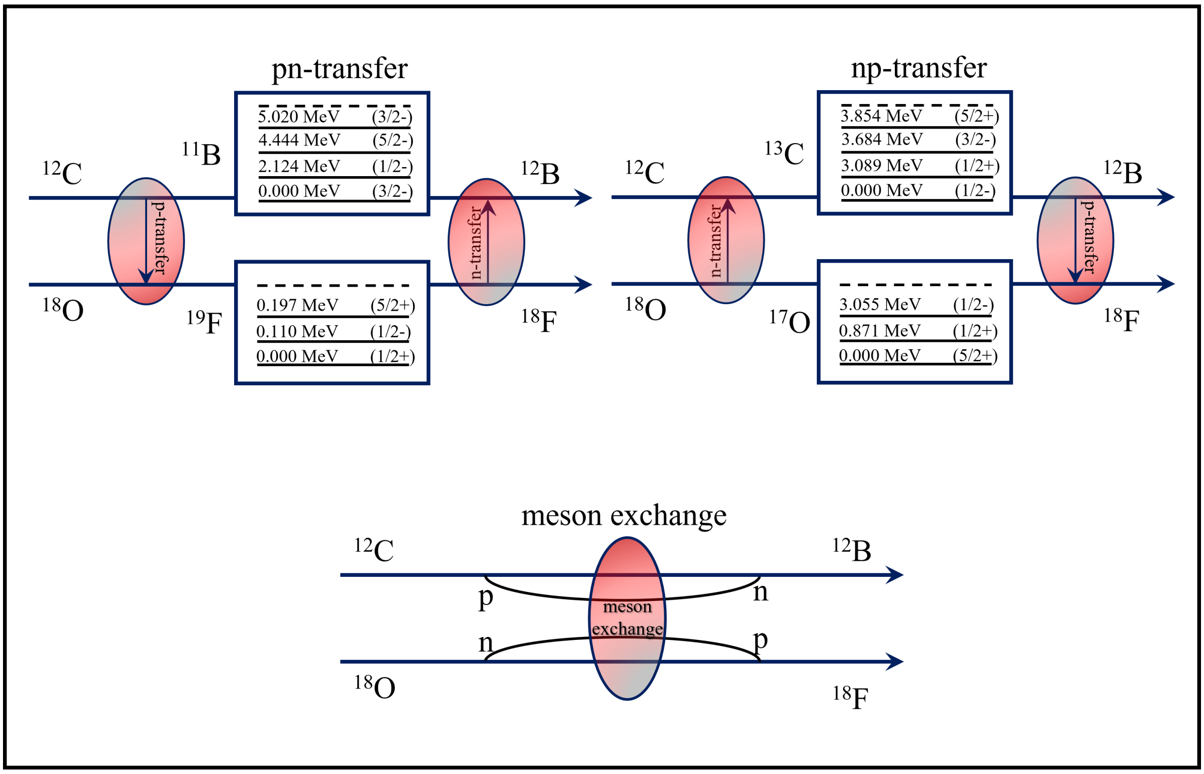

Figure 2. Schematic representation of the three reaction paths involved in the nuclear reaction analysis of the ^{12}C(^{18}O,^{18}F)^{12}B SCE nuclear reaction.

involved in the SCE nuclear reaction analysis are shown in Figure 2. The ^{12}C(^{18}O,^{19}F)^{11}B one-proton pick-up and the ^{12}C(^{18}O,^{17}O)^{13}C one-neutron stripping reaction channels were therefore analysed to constraint the single particle components of the many-body nuclear wave functions of the involved nuclei. The sequential nucleon-transfer and the direct meson-exchange are expected to play a comparable role in the full ^{12}C(^{18}O,^{18}F)^{12}B SCE reaction mechanism at 275 MeV incident energy, as stated by the authors of Refs. [18] and [19] in the case of the ^{12}C(^{7}Li,^{7}Be)^{12}B and ^{12}C(^{12}C,^{12}N)^{12}B reactions, respectively.

The description of the SCE measured cross-sections will require the not trivial coherent sum of these two components. The recent developments in Ref. [20] are highlighting the possibility to coherently perform the direct and the sequential reaction calculations simultaneously, in order to consistently treat the interference between the two reaction mechanisms inside the same (unique) calculation. Furthermore, a full-coherent study of the complete reaction mechanism implies to treat also the nuclear structure part in the same theoretical framework. This means that both the spectroscopic amplitudes for nucleon transfers and the one-body transition densities for the meson exchange processes needed to be provided in the same nuclear structure framework, i.e. large-scale shell-model, QRPA or IBM. This possibility is nowadays practicable and under study and constitutes the main promising perspective for this research.

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}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 multi-channel 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. The ^{12}C(^{18}O,^{16}O)^{14}C two-neutron transfer reaction has been already analysed and the results, recently published [21], have confirmed the observation of the giant pairing vibration (GPV). Such observation clarified how the many body nature of the pairing interaction plays a relevant role in the dynamic of the direct reactions in which pairs of nucleons are involved.

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 [10] 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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