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Abstract. The use of double charge exchange reactions is discussed in view of their application to extract information that may be helpful to determinate the nuclear matrix elements entering in the expression of neutrinoless double beta decay half-life. The strategy adopted in the experimental campaigns performed at INFN - Laboratori Nazionali del Sud and in the analysis methods within the NUMEN project is briefly described, emphasizing the advantages of the multi-channel approach to nuclear reaction data analysis. An overview on the research and development activities on the MAGNEX magnetic spectrometer is also given, with a focus on the chosen technological solutions for the focal plane detector which will guarantee the performances at high-rate conditions.

1. Introduction

Neutrinoless double-beta decay (0νββ) is a transition in which two nucleons undergo β-decay simultaneously without the emission of neutrinos or anti-neutrinos. The search for this very rare second-order electroweak process is at present one of the major challenges in particle physics since it represents the most promising way to probe neutrino properties and search for deviations from the Standard Model. In fact, 0νββ can only exist if neutrinos are Majorana particles. Furthermore, its observation would prove that total lepton number is not conserved, an observation that could be related to the unbalance between matter and antimatter in the Universe.
In this context, the knowledge of the nuclear matrix elements (NMEs) related to the wave functions of the parent and granddaughter nuclei play a fundamental role. In fact, the half-life of this process, when considering only the light neutrino exchange, may be expressed as

$$[T_{1/2}]^{-1} = G_{0\nu}|M_{0\nu}|^2|f(m_i,U_{ei},\xi_i)|^2$$

where $G_{0\nu}$ is the so-called phase-space factor, $M_{0\nu}$ is the nuclear matrix element and $f(m_i,U_{ei},\xi_i)$ is a term containing a combination of the masses m_i, the mixing coefficients U_{ei} of the neutrino species and the Majorana phases ξ_i.
However, the calculated NMEs are currently characterized by large uncertainties, with predictions from different models differing by a factor of two or three. Large efforts have therefore been devoted by the theoretical community to better constrain and improve the available nuclear structure models [1].
In this context, the NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project [2] aims at providing experiment-driven information on the NMEs involved in the expression of the decay half-life of 0νββ, by measuring the cross-sections of nuclear Double Charge Exchange (DCE) reactions [3,4]. Double charge exchange reactions are considered a powerful tool, in view of their similarities with double-β decay. The key aspects are that the two (weak and strong) processes, involve the same initial and final nuclei and are represented by transition operators that, even if different, are both a superposition of short-range isospin, spin-isospin and rank-two tensor components with a relevant available momentum (of the order of 100 MeV/c).
It is also interesting to note that, besides their connection to double-β decay, heavy ion DCE reactions are of genuine interest for nuclear structure and reaction physics, providing access to the systematic studies of the multiple excitations of elementary isovector modes of both Gamow-Teller (spin-flip) and Fermi (non-spin-flip) character.
The competition of direct and transfer mechanisms in DCE is an important issue requiring systematic experimental and theoretical studies [5]. In particular, the contribution of the transfer channels

strongly depends on the kinematical matching conditions and on the spectroscopic properties of the involved ions. Since transfer processes rely on mean-field dynamics and orbital matching conditions, their strengths can be controlled by an appropriate choice of projectile-target combinations and incident energy as observed for single charge exchange processes [4]. On the other hand, direct DCE processes are collisional processes on momentum scales defined by the masses of isovector mesons. Thus, their yields are only little affected by kinematical conditions or single particle structures.

At the time when the NUMEN project started, neither reaction nor structure theory had established methods for describing second order processes such as DCE reactions. In the last years, considerably progresses were made in developing the appropriate theory, enabling for the first time a unified description of single and double charge exchange cross sections, together with other quasi-elastic channels (scattering and nucleon-transfer channels) in a coherent multi-channel approach [6-11].

In the past few years, the NUMEN project has triggered not only a theoretical development of the appropriate formalism, numerical methods, and computer codes for the description of the SCE and DCE cross sections. NUMEN is also fostering the development of methods and technologies needed for the experimental exploration of such very suppressed reactions. The main experimental tools for the NUMEN scientific programme are the K800 Superconducting Cyclotron and MAGNEX large acceptance magnetic spectrometer installed at INFN-LNS laboratory (Italy). However, the tiny values of the measured DCE cross sections (a few nb) demand beam intensities much larger than those manageable with the present facility. Thus, the physics case of NUMEN has given the scientific motivation for a program of upgrade of the cyclotron accelerator and of the MAGNEX spectrometer to work with high intensity heavy-ion beams (up to 10^{13} pps at the target point). An intense R&D activity in beam transport, target technology, mechanical integration, detectors and electronics has been developed in the last years and is ongoing within the NUMEN project [12-15].

The aim of the present paper is not to give a comprehensive review of the full NUMEN project and activities. It can be found in refs. [2, 13, 16]. Here a focus on two of the main branches of the NUMEN activity will be given. One, described in Section 2, is the multi-channel approach to the data interpretation, which covers both the experimental strategy and the theoretical analysis. The second, reported in Section 3, is an overview of the research and development activities on the MAGNEX magnetic spectrometer focal plane detectors, with a focus on the chosen technological solutions which will guarantee the performances at high-rate conditions.

2. The multi-channel approach

In DCE reactions, as a typical feature of all direct reactions, the cross sections critically depend on the ion-ion initial and final state interaction, which in leading order determines the cross section for elastic scattering. Also, the coupling of different reaction channels could play an important role for accurate studies of the reaction cross sections and should be studied in detail. In addition, also the nuclear structure inputs have impacts of the estimation of the reaction cross sections. Such a connection between a specific reaction channel with the elastic and other quasi-elastic processes makes it necessary to study such processes in a common approach, where different reaction channels are studied at the same time.

The actual implementation of this multi-channel approach for the study of heavy-ion induced reactions has been rarely used in the analyses of data, mainly due to the complexity of the problem from both the experimental and theoretical side. From the experimental side different reaction cross section should be measured under the same laboratory conditions. From the theory side a high degree of consistency is required in order to simultaneously treat the different degrees of freedom selectively activated by the various direct reactions in the same approach.

A clear advantage of the multi-channel approach is the possibility to use a broad and correlated ensemble of experimental data in the analyses, thus reducing the need of free parameters in the adopted theoretical models. This is particularly relevant when the reaction of interest has a very small cross section, as it occurs for DCE reactions, since effects such as the channel couplings could be important for the description of the data.

For such reasons the NUMEN project is implementing a multi-channel approach where DCE cross sections are analysed together with elastic scattering, inelastic scattering, single and multi-nucleonic transfer reactions and SCE reactions. The analysis of each reaction channel allows to access the many features of the dynamical process and the structure of the colliding nuclei involved in the DCE reaction:

- Elastic and inelastic scattering to investigate nucleus-nucleus potential and nuclear deformation, respectively. The initial and final state interactions (and the ones relative to the intermediate partitions) are responsible for the distortion of the incoming and outgoing wave functions involved in nuclear reactions and play a central role in the reaction mechanisms.
- One-nucleon transfer reactions to access the single-particle configurations in nuclear states. The occupation probabilities of valence orbits active in the decay and reaction dynamics is one of the most relevant features of the nuclear wave functions.
- Two-nucleon transfer reactions, very sensitive probes to specific nuclear many-body properties, such as the pairing interaction.
- Single charge exchange reaction analysis, crucial to constrain the double-single charge exchange contribution to the total DCE cross section.

A case where such a multi-channel approach has been applied is the exploration of the ^{18}O + ^{40}Ca collision at 15 MeV/u. This system represents the pilot case in the NUMEN project and is the first system that has been studied in a comprehensive approach both from the experimental and theoretical side. Fig. 1 schematically depicts the network of nuclear reactions explored in the multi-channel study of this system.

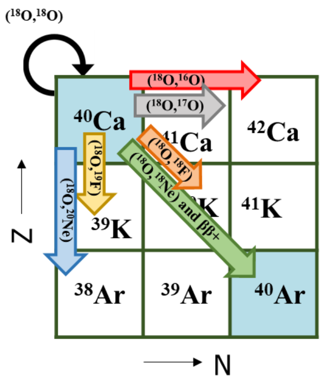

Figure 1. Networks of nuclear reactions explored in the ^{18}O+^{40}Ca collision

The elastic and inelastic channels have been analysed in a recent work [9]. Fig. 2 summarizes the obtained results, in which one-channel calculations fail to reproduce the cross sections at large angles. Coupled-channel calculations (CC), using the standard prescription for the scaling factor for the imaginary part of the optical potential, N_W = 0.78, provides a good description of both elastic and inelastic angular distributions in a unique reaction framework and without the need of adjusting free parameters. In addition, following the approach of [17], we introduced an effective polarization potential term, through an average local and L-independent polarization potential, named trivially equivalent local potential (TELP), which implicitly incorporates the effect of channel couplings in the elastic optical potential. Adding the TELP to the SPP bare optical potential used in CC calculations, a coupled channel equivalent polarization potential (CCEP) is extracted, which has been used in the one-channel calculations shown in Fig. 2, producing a good agreement with data and avoiding the complications raising from higher order calculations. The use of a CCEP, not necessary for elastic scattering calculations, can be important in view of its application to the description of more complex reaction mechanisms such a s SCE and DCE.

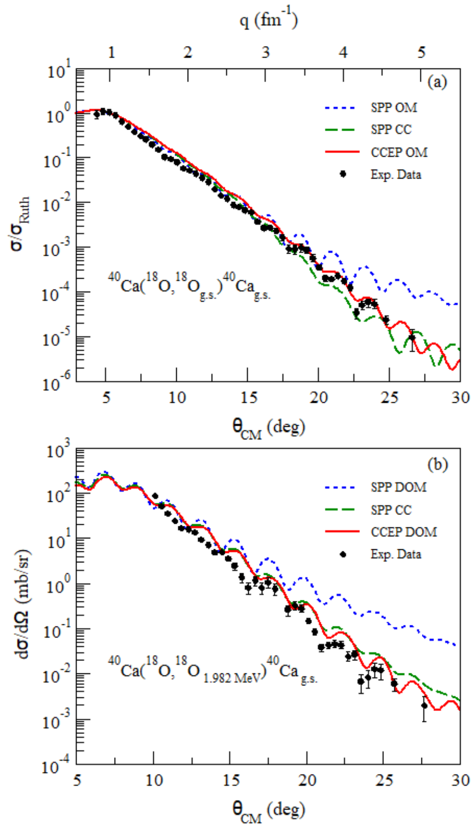

Figure 2. Panel (a): Cross section angular distribution of the $^{18}O+^{40}Ca$ elastic scattering at 15 MeV/u in terms of its ratio to the Rutherford cross section. Panel (b): Angular distribution of the inelastic channel $^{40}Ca(^{18}O,^{18}O_{1.982})^{40}Ca_{g.s.}$. In both plots, the blue dotted line shows the optical model (OM) and distorted wave Born approximation (DOM) calculations with the SPP, the green dashed line shows the CC calculations with SPP, and the red solid line shows the OM and DOM calculations with CCEP. From Ref. [9].

In the same experimental run, the one- and two-nucleon transfer channels populated in the ^{18}O + ^{40}Ca collision have been measured. The details of analysis of the one-nucleon transfer reactions have been reported in ref. [18] while the two-proton transfer reaction has been studied in ref. [19]. Reaction calculations using shell model spectroscopic amplitudes and initial state interaction derived from the elastic/inelastic scattering analysis previously performed provide an excellent description of the data, confirming that both the reaction inputs and the nuclear structure information are in place for a reliable description of the one-nucleon transfer.
The $^{40}Ca(^{18}O, ^{18}F)^{40}K$ single charge exchange reaction has also been explored in a consistent way. Details on the experiment and analysis are given in ref. [9]. Charge exchange cross section calculations have been performed in DWBA using the CCEP tested against the scattering data and form factors extracted from double folding of a nucleon–nucleon isovector interaction with QRPA transition densities. Such full quantum-mechanical calculations describe the order of magnitude and shape of the observed cross sections. In the low excitation energy region, the calculations slightly underestimate the experimental cross section, leaving room for a contribution from the sequential two-step contribution as shown in ref. [16]. An analysis which contains the structure inputs from the same shell model calculations used in the nucleon-transfer data is still ongoing.
Other systems already explored within the NUMEN schedule applying the multi-channel analysis are the $^{20}Ne+^{116}Cd$ [10, 11, 19, 20], $^{18}O+^{48}Ti$ [21], $^{18}O+^{12}C$ [22], $^{18}O+^{76}Se$ [23] collisions.

3. The upgrade of the experimental facility

An intense R&D activity has been performed within the NUMEN project to improve the existing MAGNEX facility and allow to work with the new high intensity heavy ion beams delivered by the upgraded LNS superconducting cyclotron [14].

The upgrade of the MAGNEX spectrometer will mainly involve the beam lines at the entrance and exit of MAGNEX [13, 14], the scattering chamber [24] and the focal plane detector chamber [13], the target system [25], the focal plane detector [13], the coupling of the spectrometer with a new gamma array detector placed around the target point [13]. A comprehensive description of the requests and of the choices made during the R&D activity has been recently published within the NUMEN Technical Design Report [13]. In the present section, a focus on the focal plane detector is given.

A gas tracker for the new focal plane detector of the MAGNEX spectrometer is under development. The role of the tracker is to perform a three-dimensional measurement of the reaction ejectile trajectories crossing the focal plane [26, 27]. Such an operation is needed for particle identification purposes and to allow the high-order reconstruction of the trajectories. Two main characteristics are required. The first is a high-resolution measurement of the phase space parameters of the ion tracks at the focal plane. The required resolution is better than 0.6 mm for the position measurement and lower than 5 mrad for angle. The second requirement is the ability to withstand the expected high rate of impinging particles (about 50 kHz/cm).

The new tracker will have an active volume of 1200 x 150 x 108 mm^3. A reduced size prototype has been developed and built during the R&D phase of NUMEN. This prototype has mechanical and electrical features very similar to those of the final tracker, except for a shorter length which allows easier tests in a small gas chamber. The voltages applied at the electrodes, the gas pressure and flowing system, the multiplication technology, and the front-end electronics are among the main features tested with the reduced-size prototype. The prototype, as well as the full-size detector, works as a time projection chamber and consists of three main sections:

- a drift region, which is the active volume of the detector, crossed by the ejectiles of interest, delimited by a cathode and a multiplication electrode,
- an electron multiplication electrode, based on the technology of multiple Thick Gas Electron Multipliers (m-THGEM) [28],
- a segmented read-out electrode, connected with electronics, where the charge distribution of the secondary electrons is collected and information on the horizontal position and angle are extracted.

Results from the prototype characterization in terms of measured currents and of different segmentation geometries for the anodic read-out plate are given in [13, 29].

The new gas tracker of the MAGNEX spectrometer is not designed to provide accurate information on ion energy loss. Consequently, particle identification (PID) must be assigned to a dedicated wall of telescope detectors downstream of the tracker. The PID wall must be capable of unambiguously identifying ions in the region of interest for NUMEN ejectiles (typically O, F and Ne). Moreover it must guarantee radiation hardness (the heavy-ion fluence rate will be of the order of 10^{11} ions/cm^2·yr), energy resolution (better than 2%), time resolution (~5 ns, to guarantee an accurate measurement of the drift time of the primary electrons in the gas tracker), a certain degree of segmentation (to keep the pile-up probability below 3% in the whole FPD), good geometrical efficiency (which should be high enough to obtain an accurate measurement of the absolute cross section and to reduce the background from events with partial charge collection). In addition, the detector thickness must be enough to stop the ejectiles of interest in a wide dynamical range of incident energies, typically 15 to 60 MeV/u and it must work in a low-pressure gas environment (typical pressure 10-100 mbar).

The R&D activity on the PID wall finalized in the choice of an array of two-stage telescopes of Silicon Carbide (SiC) [30] and Thallium-doped Cesium Iodide CsI(Tl) detectors. The active area of each element is 1.5 × 1.5 cm^2. The SiC detector is 100-μm thick, while the CsI(Tl) scintillator is 5-mm thick and is coupled to a Hamamatsu S3590 photodiode with a 1 × 1 cm^2 area. The capabilities of the system in terms of radiation hardness and mass resolution are discussed in ref. [12]. In particular, SiC detectors are expected to feature a better radiation hardness with respect to silicon detectors (Si) due to a larger band gap (3.23 eV for SiC, 1.12 eV for Si) and a larger displacement energy (30 to 40 eV for SiC and 13 to 15 eV for Si).

4. Conclusions and perspectives

The aim of NUMEN is to investigate the nuclear response to DCE reactions for all the isotopes explored by present and future studies of 0νββ decay. Several aspects of the project require the development of innovative techniques for the experiment set-up, the detection system and the theoretical interpretation of the collected data. Indeed, following the upgrade, the INFN-LNS facility is likely to become unique for this research in a worldwide context.
NUMEN is not only a challenging project at the intersection of nuclear and neutrino physics, driven by an important physics case and opening interesting scientific scenarios on our current understanding of fundamental physics. It also has a genuine nuclear physics interest, since it allows to collect a wide set of new experimental data on several heavy-ion induced reactions and to perform a coherent and constrained multi-channel analysis of such data. Moreover, it also opens potential technological spillovers, as is the case with the SiC technology. Due to its radiation hardness and resistance to high temperatures, SiC can replace silicon for several applications in harsh environments: it can be employed in dosimeters, or as a lower cost and larger area replacement of diamond detectors in nuclear industry, not to mention the enormous potential envisaged in the automotive sector. Similarly, other technological developments done during the NUMEN R&D activity can be useful for different applications outside the fundamental research field, as for instance the thin targets production techniques, cryogenics, robotic manipulation, electronics, and high throughput data handling.

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