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Recent results on heavy-ion direct reactions of interest for 0νββ decay at INFN - LNS

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Abstract. Neutrinoless double beta decay of nuclei, if observed, would have important implications on fundamental physics. In particular it would give access to the effective neutrino mass. In order to extract such information from 0νββ decay half-life measurements, the knowledge of the Nuclear Matrix Elements (NME) is of utmost importance. In this context the NUMEN and the NURE projects aim to extract information on the NME by measuring cross sections of Double Charge Exchange reactions in selected systems which are expected to spontaneously decay via 0νββ. In this work an overview of the experimental challenges that NUMEN is facing in order to perform the experiments with accelerated beams and the research and development activity for the planned upgrade of the INFN-LNS facilities is reported.

1. Introduction

Neutrinoless double beta decay (0νββ) of atomic nuclei is a predicted but still unobserved spontaneous decay which is attracting a deep interest in the physics community. The main reason is that its observation would establish the Majorana nature of neutrino and would shed light on the absolute neutrino mass and hierarchy. In addition, this phenomenon could provide precious information to interpret key problems of fundamental physics as the unification of the fundamental forces and the matter-antimatter balance in the Universe [1].

A critical aspect of 0νββ physics is associated to the determination of the Nuclear Matrix Elements (NME) entering in the expression of the decay half-life. These quantities must be known with good accuracy, despite the intrinsic many-body nature of the parent and daughter nuclei makes this task

particularly hard. There are no experimental methods to directly measure 0νββ NMEs and state of the art theoretical calculations lead to discrepancy factors larger than two. In addition, some assumption common to different nuclear structure approaches could cause overall systematic uncertainties. Thus experimentally driven inputs relevant to understand the 0νββ responses are useful to help evaluate the 0νββ NMEs and to constrain the existing calculations.

In this context, the NUMEN [2], [3] and NURE [4] projects at INFN-LNS Catania aim to study heavy-ion induced single (SCE) and double (DCE) charge exchange reactions in a systematic approach, with the intention to extract information on NMEs for single and double charge exchange processes and to identify the possible connections with 0νββ.

Despite 0νββ decays and DCE reactions are mediated by different interactions, they present several similarities. Among those, the key aspects are that initial and final nuclear states are the same and the transition operators in both cases present a superposition of short-range isospin, spin-isospin and rank-two tensor components with a sizeable available momentum (≈100 MeV/c).

2. The NUMEN phases

The NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project is conceived in the view of a comprehensive study of many candidate systems for 0νββ decay. Moreover, this project promotes and is strictly connected with the upgrade of the INFN-LNS research infrastructure (POT-LNS) and with a specific R&D activity on detectors, materials and instrumentation.

NUMEN is structured into four phases:

- Phase 1: *"The pilot experiment"* - In 2013, the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar DCE reaction was measured at INFN-LNS together with the competing processes: ^{40}Ca(^{18}O,^{18}F)^{40}K SCE, ^{40}Ca(^{18}O,^{20}Ne)^{38}Ar two-proton transfer and ^{40}Ca(^{18}O,^{16}O)^{42}Ca two-neutron transfer [5]. This work showed for the first time high resolution and statistically significant experimental data on DCE reactions in an wide range of transferred momenta. The measured angular distribution is characterized by an oscillating shape, well described by an L = 0 Bessel function, indicating that in the DCE reaction a simple mechanism should be dominant. This is confirmed by the observed suppression of the multi-nucleon transfer routes. DCE NMEs were extracted under the hypothesis of a two-step charge exchange process. Despite the approximations used in our model, which determine an uncertainty of ±50%, the obtained results are compatible with the values known from literature, indicating that the main physics content has been kept.
- Phase 2: *"From the pilot experiment toward the hot cases"* – Based on the feasibility studies of Phase 1, during Phase 2 (presently on going) a few selected isotopes of interest for 0νββ are being studied by DCE reactions and competing quasi-elastic reactions, as reported in Section 3. The experimental activity with accelerated beams of Phase 2 is part of a project funded by European Research Council named NURE (NUclear REactions for neutrinoless double beta decay).

  The results of experiments performed in Phase 1 and 2 indicate that suitable information from DCE reactions can be extracted. However the low yields of the measured data and the long beam time needed (typically one month) suggest that the DCE experiments should be performed with higher beam current, two orders of magnitude higher than the present. Therefore, the present limits of beam power for the cyclotron accelerator (∼100 W) and of acceptable rate for the MAGNEX focal plane detector (few kHz) [6] must be sensibly revised. This goal will be achieved by a substantial change in the technologies implemented in the beam extraction [7], in the detection of ejectiles and in target cooling systems [8], [9]. During Phase 2, such R&D activities is being performed, as introduced in Section 4. The development of the theory necessary to describe nuclear cross sections of DCE, SCE, transfer, elastic and inelastic channels is also pursued during Phase 2 [10], [11], [12] but is not the topic of this work.
- Phase 3: *The Facility Upgrade* - During Phase 3 the old MAGNEX set-up will be disassembled and the new one assembled. During this period, the data analysis of the NUMEN Phase 2

experiments will continue. In addition, tests of the new detectors and selected experiments will be performed in other laboratories in order to provide possible missing information.

- Phase 4: *"The Experimental Campaign with Upgraded Facility"* - The Phase 4 will consist of an experimental campaign at high beam intensities (particle-μA) and integrated charge of hundreds of mC up to C, spanning all the 0νββ decay candidate isotopes, such as: ^{48}Ca, ^{76}Ge, ^{76}Se, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{106}Cd, ^{110}Pd, ^{116}Cd, ^{110}Sn, ^{124}Sn, ^{128}Te, ^{130}Te, ^{136}Xe, ^{130}Xe, ^{148}Nd, ^{150}Nd, ^{154}Sm, ^{160}Gd, ^{198}Pt. Hopefully, the use of improved theoretical analyses will give access to the NMEs, thus fulfilling the most ambitious goal of NUMEN.

3. The experimental activity with accelerated beams during Phase 2

Important experimental challenges must be addressed to measure heavy ion induced DCE reactions.

Such challenges are related to the request to detect heavy ions with good isotopic separation and energy resolution in a wide angular range, including zero-degree, in order to distinguish transitions to individual states and explore a wide momentum transfer range.

In addition, the need to measure small DCE cross sections (few nb) requires a challengingly high experimental sensitivity, which strongly depend on the rejection capability against unwanted events generated by competing reaction processes [13]. For this reason, high resolution particle identification is a prerequisite for the experiment.

Experimentally, the main tools for this project are the high resolution Superconducting Cyclotron beams and the MAGNEX magnetic spectrometer [14], [15]. The latter is a large acceptance magnetic system able to provide high resolution in energy, mass and angle and an accurate control of the detection efficiency. The implementation of trajectory reconstruction technique is the key feature of MAGNEX, which guarantees the above mentioned performance and its relevance in the research for heavy-ion physics [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], also taking advantage of its coupling to the EDEN neutron detector array [27], [28].

The experimental activity with accelerated beams presently in progress consists of two main classes of experiments, corresponding to the exploration of the two directions of isospin lowering $\tau^-\ \tau^-$ and rising $\tau^+\ \tau^+$, characteristic of $\beta^-\beta^-$ and $\beta^+\beta^+$ decays, respectively [29].

In particular, the $\beta^+\beta^+$ direction in the target is investigated using an $^{18}O^{8+}$ beam and measuring the (^{18}O,^{18}Ne) DCE transitions, together with other reaction channels involving same beam and target. Similarly, the $\beta^-\beta^-$ direction is explored via the (^{20}Ne,^{20}O) reaction, using a $^{20}Ne^{10+}$ beam and detecting the reaction products of the DCE channel and of the other open channels characterized by same projectile and target.

Exploratory investigations of the two classes of experiments and for the competing quasi-elastic channels have been already performed, highlighting the strengths and the limiting aspects of the adopted technique and establishing the best working conditions [29], [30], [31], [32].

3.1. Experiments with ^{18}O projectiles ($\beta^+\beta^+$ direction)

For the experiments of this class, the reaction channels of interest are listed below:

- Elastic and inelastic scattering (^{18}O,^{18}O)
- DCE reaction (^{18}O,^{18}Ne)
- Charge-exchange reaction (^{18}O,^{18}F)
- Two-proton pickup reaction (^{18}O,^{20}Ne)
- One-proton pickup reaction (^{18}O,^{19}F)
- Two-neutron stripping reaction (^{18}O,^{16}O)
- One-neutron stripping reaction (^{18}O,^{17}O)

One of the main challenges of such experiments is the measurement at very forward angles, including zero-degree. This is performed by placing the spectrometer with its optical axis at +3° with respect to the beam axis. Thanks to its large angular acceptance, a range $0° < \theta_{lab} < +9°$ is thus covered. The MAGNEX quadrupole and dipole magnetic fields are set in order that the incident beam, after passing

through the magnets, reaches a region besides the FPD where it stops in a specifically designed Faraday Cup, which measures the incident charge in each run.

^{116}Sn, ^{76}Se and ^{48}Ti are the targets already explored via (^{18}O,^{18}Ne) reaction at 15 and 22 AMeV in order to study the ^{116}Sn → ^{116}Cd, ^{76}Se → ^{76}Ge and ^{48}Ti → ^{48}Ca transitions, respectively, and the competing channels. The reduction and analysis of the collected data is presently in progress.

3.2. Experiments with ^{20}Ne projectiles ($\beta^-\beta^-$ direction)

In the class of experiments with $^{20}Ne^{10+}$ beams, the reaction channels we are interested are the following:
- Elastic and inelastic scattering (^{20}Ne,^{20}Ne)
- DCE reaction (^{20}Ne,^{20}O)
- Charge Exchange reaction (^{20}Ne,^{20}F)
- Two-proton stripping reaction (^{20}Ne,^{18}O)
- One-proton stripping reaction (^{20}Ne,^{19}F)
- Two-neutron pickup reaction (^{20}Ne,^{22}Ne)
- One-neutron pickup reaction (^{20}Ne,^{21}Ne)

For these experiments, the spectrometer optical axis is typically placed at −3°, thus the covered angular range is $0° < \theta_{lab} < +8°$. The quadrupole and dipole magnetic fields of MAGNEX are set in order that the $^{20}Ne^{10+}$ beam reaches the low-Bρ region besides the FPD where a specific Faraday cup is located.

A peculiarity of these experiments concerns the treatment of the different charge states of the beam emerging out of the target. The beam components characterized by charge states lower than 10^+, mainly $^{20}Ne^{9+}$ and $^{20}Ne^{8+}$, produced by the interaction of the beam with the electrons of the target material, have a magnetic rigidity which is similar to the ions of interest. Therefore, they enter in the FPD acceptance, causing a limitation in the rate tolerable by the detector. In order to stop these unwanted ^{20}Ne particles, two aluminium shields are mounted upstream the sensitive region of the focal plane detector. Moreover, a specific study of different materials to be used as post-stripper foil downstream of the target foil to conveniently minimize the amount of $^{20}Ne^{9+}$ and $^{20}Ne^{8+}$ has been recently performed [30].

The systems already explored using the (^{20}Ne,^{20}O) reaction at 15 AMeV are the ^{116}Cd target (to study the ^{116}Cd → ^{116}Sn transition), the ^{130}Te (for the ^{130}Te → ^{130}Xe) and the ^{76}Ge (for the ^{76}Ge → ^{76}Se), together with the elastic, inelastic, SCE and transfer reactions involving same beams and targets. The data reduction and analysis are in progress.

4. The R&D activity during Phase 2

The main foreseen upgrades for the spectrometer whose R&D activities are being performed within Phase 2 are:

- The substitution of the present focal plane gas tracker, based on multiplication wire technology, with a tracker system based on micro patterned gas detector [33];
- The substitution of the wall of silicon pad stopping detectors with telescopes of SiC-CsI detectors [34], [35];
- The introduction of an array of scintillators for measuring the coincident γ-rays [36], [37];
- The enhancement of the maximum accepted magnetic rigidity, preserving the geometry and field uniformity of the magnetic field in order to keep the high-precision of the present trajectory reconstruction;
- The design and installation of a beam dump to stop the high-power beams, keeping the generated radioactivity under control [38].
- The development of the technology for suitable nuclear targets to be used in the experiments. Here the challenge is to produce and cool isotopically enriched thin films able to resist to the high power dissipated by the interaction of the intense beams with the target material [8], [9].

5. Conclusions

A systematic study of heavy-ion induced double charge exchange reactions and of the other reaction channels characterized by the same projectile and target is in progress at INFN-LNS. The main goal is to investigate the nuclear response to DCE reactions for all the isotopes candidate for 0νββ decay to give experimentally driven indication towards the determination of 0νββ NMEs.
In the present paper, the focus is on the techniques adopted to set up the MAGNEX spectrometer for the challenging measurements of such suppressed reaction channels. The strategy used to perform the zero-degree measurement, based on an accurate simulation of the ion trajectories along the spectrometer and on the use of two Faraday cups properly designed for each category of experiments is described. The R&D activities presently on going on the beam lines and MAGNEX spectrometer are also briefly described.

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