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NUMEN aims at accessing experimentally driven information on Nuclear Matrix Elements (NME) involved in the half-life of the neutrinoless double beta decay (0νββ), by high-accuracy measurements of the cross sections of Heavy Ion (HI) induced Double Charge Exchange (DCE) reactions. First evidence about the possibility to get quantitative information about NME from experiments is found for the (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) reactions. Moreover, to infer the neutrino average masses from the possible measurement of the half-life of 0νββ decay, the knowledge of the NME is a crucial aspect. The key tools for this project are the high resolution Superconducting Cyclotron beams and the MAGNEX magnetic spectrometer at INFN Laboratori Nazionali del Sud in Catania (Italy). The measured cross sections are extremely low, limiting the present exploration to few selected isotopes of interest in the context of typically low-yield experimental runs. A major upgrade of the LNS facility is foreseen in order to increase the experimental yield of at least two orders of magnitude, thus making feasible a systematic study of all the cases of interest.

KEYWORDS: Heavy Ions Double Charge Exchange reactions, neutrinoless double beta decay, Nuclear Matrix Elements, Nuclear Reactions, Nuclear structure, magnetic spectrometer, cyclotron, NUMEN project

1. Introduction

The search for neutrinoless double beta decay (*0νββ*) addresses fundamental questions in physics, related to the absolute neutrinos mass scale, whether neutrinos are Majorana particles or how many neutrino species are there. Moreover *0νββ* search has implications for the understanding of the matter-antimatter asymmetry in the universe. The design of the *0νββ* search experiments themselves require detailed understanding of nuclear physics, as backgrounds critically depend on nuclear decay chain and nuclear matrix elements are needed to link observed rates to neutrino properties.

In this framework the NUMEN project proposes an innovative and original tool: to use HI-DCE reactions to access quantitative informations for NME towards *0νββ* decay.

2. The NUMEN project

The NUMEN main goal is the extraction from measured cross-sections of "data-driven" information on NME for all systems candidate for *0νββ*. Crucial for the experimental challanges is the INFN LNS facility, made by the CS and the MAGNEX magnetic spectrometer. The experimental measurements of HI-DCE reactions present a number of challenging aspects, since they are characterized by very low cross sections and, in the same experimental conditions, had to be isolated among the different competitive reaction channels.

It is well known that the *0νββ* half-life can be factorized in three terms at different physics scale: the phase-space factor, connected with Atomic physics, the Matrix Element (NME) related with Nuclear physics and a term, related to Particle physics, in which it is supposed there are the answers to the unsolved questions, related to new physics beyond the Standard Model. For evaluation of NME several methods have been used, based on different nuclear models, an updated comparison of the results of NME calculations, obtained within various nuclear structure frameworks [1-4], indicates that significant differences are indeed found. In addition, some assumption common to different competing approaches could cause overall systematic uncertainties.

NUMEN [5, 6] proposes a novel way to address experimentally-driven information on the NMEs of *0νββ,* based on DCE cross section measurements. These reactions are characterized by the transfer of two charge units, leaving the mass number unchanged, and can proceed either by a sequential multi-nucleon-transfer mechanism or by meson-exchange. Despite *0νββ* decays and HI-DCE reactions are mediated by different interactions, they present a number of similarities, among the others: the initial and final state wave functions in the two processes are the same.

MAGNEX is a large acceptance magnetic system able to provide high resolution in energy, mass and angle [7] 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 [8-10], also taking advantage of its coupling to the EDEN neutron detector array [11,12]. At the this facility we demostrate the feasibility of this kind of DCE cross sections measurements, with ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction, that was studied at 15 MeV/u, see ref. [13]. This result demonstrated that the previous experimental limitations are almost overcome and that high resolution and statistically significant experimental data can be measured for DCE processes. In the present experimental conditions, due to the limitation arising from the tiny cross-sections of the processes of interest, only very few systems can be measured. In order to systematically explore all the nuclei candidates for *0νββ*, a beam intensity at least two orders of magnitude higher than the present must be achieved. NUMEN is conceived in a long-range time perspective, in view of a comprehensive study of many candidate systems for *0νββ* decay. Moreover, the project promotes a renewal of the INFN-LNS research infrastructure with a specific R&D activity on the accelerator, the detectors, materials and instrumentation. For the accelerator the change of the beam extraction technology from electrostatic deflector to a stripper foil is an adequate choice [14]. For the spectrometer the main foreseen upgrades are:

1. The substitution of the present focal plane detector (FPD) gas tracker, based on multiplication wire technology with a tracker system based on micro patterned gas detector [15,16];
2. The substitution of the wall of silicon pad stopping detectors with telescopes of SiC-CsI detectors [17,18] or similar [19];
3. The introduction of an array of scintillators for measuring the coincident γ-rays [20], using the experience on studies of different scintillators materials [21];
4. The development of suitable front-end and read-out electronics, capable to guarantee a fast read-out of the detector signals, still preserving a high signal to noise ratio and guaranteeing enough hardness to radiation [22,23];
5. Develop a suitable architecture for data acquisition, storage and data handling, including accurate detector response simulations;
6. The enhancement of the maximum accepted magnetic rigidity, preserving the geometry and field uniformity of the magnetic field [24-25] in order to keep the high-precision of the present trajectory reconstruction;
7. The installation of a beam dump to stop the high power beams, keeping the generated radioactivity under control.

In addition, we are developing 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 [26-27].

Moreover, a deep and complete investigation of the theoretical aspects connecting nuclear reaction mechanisms and nuclear matrix elements must be carried out [28, 30]. With the present facility and experimental setup we perform some long run at LNS with MAGNEX, choosing few isotopes, candidates for $0\nu\beta\beta$, already at our reach in terms of energy resolution and availability of thin targets. In particular, we performed for the first time experimental investigations of the (^{20}Ne,^{20}O) DCE reaction on ^{116}Cd,^{76}Ge and ^{130}Te targets. These are the first measurements of such a kind of reaction: no data are available in literature. For the ^{116}Cd-^{116}Sn and ^{76}Ge-^{76}Se pairs, the ground states are resolved from excited states by MAGNEX for both (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) reactions [31]. Despite the experimental limitations, we were able to measure energy spectra and absolute cross sections for the DCE reaction channel. Moreover, we measured also other reaction channels: one- and two-proton transfer, one- and two-neutron transfer and Single Charge Exchange, in order to estimate the role of the sequential multi-nucleon transfer routes on the diagonal DCE process.

3. Conclusion

Pioneering experiments on (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) DCE performed at INFN-LNS in Catania have shown that accurate cross sections measurements at very forward angles can be done. The main activity characterizing the NUMEN project is the measurement of DCE absolute cross sections, with the related processes, and the extraction of relevant NMEs. The NUMEN "Holy Graal" is to find a connection between the NMEs extracted from DCE reactions and those characterizing $0\nu\beta\beta$ decay. NUMEN is a big challenge both for nuclear technology and nuclear theory. Moreover it promotes an important upgrade of the experimental facilities and the development of the different theoretical aspects, connected with the nuclear structure and reaction mechanisms, involved in heavy ions induced in DCE reactions. High intensity beams are the new frontier for these challenging studies. NUMEN indicates a possible growth prospect of heavy-ion physics in synergy with neutrino physics, aims at giving an innovative contribution in one of the most promising fields of fundamental physics.

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