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Recent results on Heavy−Ion induced reactions of interest for *0νββ* decay

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Abstract. An updated overview of recent results on Heavy-Ion induced reactions of interest for neutrinoless double beta decay is reported in the framework of the NUMEN project. The NUMEN idea is to study heavy-ion induced Double Charge Exchange (DCE) reactions with the aim to get information on the nuclear matrix elements for neutrinoless double beta (0νββ) decay. Moreover, to infer the neutrino average masses from the possible measurement of the half- life of 0νββ decay, the knowledge of the nuclear matrix elements is a crucial aspect.

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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 background 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 propose an innovative and original tool: to use Heavy-Ions Double Charge Exchange Reactions (HI-DCE) to access quantitative information for Nuclear Matrix Element towards *0ββ* decay.

2. The NUMEN Project

The NUMEN main goal is the extraction from measured cross-sections of "data-driven" information on Nuclear Matrix Elements for all the systems candidate for *0νββ*. Crucial for the experimental challanges is the INFN Laboratori Nazionali del Sud (LNS) facility, made up by the Superconducting Cyclotron (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, they must be identified with respect to 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] propose 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. The main ones are:

i) the initial and final state wave functions in the two processes are the same,
ii) the transition operators are similar, in both cases Fermi, Gamow-Teller and rank-two tensor components are present,
iii) a large linear momentum (100 MeV/c) is available in the virtual intermediate channel,
iv) the two processes are non-local and are characterized by two vertices localized in a pair of valence nucleons,
v) they take place in the same nuclear medium,
vi) a relevant off-shell propagation through virtual intermediate channels is present.

The descriptions of NMEs for DCE and 0νββ decay present the same degree of complexity, with the advantage for DCE to be "accessible" in laboratory. However, a simple relation between DCE cross sections and 0νββ decay half-lives is not trivial and needs to be explored.

At the MAGNEX facility of the INFN-LNS we demostrate the feasibility of this kind of DCE cross sections measurements. 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]. The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ reaction was studied at 15 MeV/u, showing that high mass, angular and energy resolution energy spectra and accurate absolute cross sections are at our reach, even at very forward angles, see ref. [13]. In addition, a schematic analysis of the reaction cross sections demonstrated that relevant quantitative information on DCE matrix elements can be extracted from the data. 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 within the 5-years project. In order to systematically explore all the nuclei candidates for $0\nu\beta\beta$, a beam intensity at least two orders of magnitude higher than the present must be achieved.

The NUMEN project is conceived in a long-range time perspective, in view of a comprehensive study of many candidate systems for $0\nu\beta\beta$ decay. Moreover, the project promotes a renewal of the INFN-LNS research infrastructure [14] with a specific R&D activity on detectors, materials and instrumentation. As a consequence, major upgrades of the detector technologies (3D ion tracker, particle-identification wall, gamma-ray array, ...) must be developed [15, 20]. Also the target technology must be upgraded, to avoid the damage of the thin films due to the high temperature involved [21, 23]. Moreover, a deep and complete investigation of the theoretical aspects connecting nuclear reaction mechanisms and nuclear matrix elements must be carried out [24, 26].

2.1. An updated overview

NUMEN experimental activity consists of two main classes of experiments, corresponding to the exploration of the two directions of isospin transfer $\tau^-\tau^-$ and $\tau^+\tau^+$, characteristic of $\beta^-\beta^-$ and $\beta^+\beta^+$ decays, respectively. In particular, the $\beta^+\beta^+$ direction in the target is investigated using a ^{18}O beam and measuring the ($^{18}O,^{18}Ne$) DCE induced transitions, together with the other reaction channels involving the same beam and target. Similarly, the $\beta^-\beta^-$ direction is explored via the ($^{20}Ne,^{20}O$) reaction, using a ^{20}Ne beam and detecting the reaction products of the DCE channel along with other open channels characterized by the same projectile and target. With the actual 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. A $^{20}Ne^{10+}$ cyclotron beam at 15 AMeV was delivered by the CS of INFN-LNS and impinged on ^{116}Cd rolled target of 1370 μg/cm^2 thickness and ^{76}Ge (386 μg/cm^2 thickness) and ^{130}Te (247 μg/cm^2 thickness) both evaporated on a C backing of 50 μg/cm^2. The thickness of the various targets was carefully chosen in order to obtain an energy resolution which allows to distinguish the transition to the residual nucleus ground state from its first excited state. Indeed, the selected thickness of ^{116}Cd is much higher than that of ^{76}Ge and ^{130}Te, because the first excited state in ^{116}Sn case is at 1.293 MeV, to be compared to 0.559 MeV in ^{76}Se and 0.536 MeV in ^{130}Xe. The MAGNEX spectrometer was placed at forward angles including zero degrees in the full acceptance mode (50 msr). 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.

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3. Conclusions and outlook

Pioneering experiments on (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) DCE performed at INFN-LNS Laboratory 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 Grail" is to find a connection between the NMEs extracted from DCE reactions and those characterizing $0\nu\beta\beta$ decay, at least in the nuclei in which this process is energetically allowed. 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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