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Abstract. 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. The idea is to use as experimental tool Heavy Ions –Double Charge Exchange (HI-DCE) reactions. Crucial for the experimental challanges is the INFN Laboratori Nazionali del Sud (LNS) facility, made 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. Here it is reported the new experimental campaign of NUMEN Project.

1. INTRODUCTION

The connection between nuclear structure and physics of neutrinoless double beta (0νββ) decay has important implications on particle physics, cosmology and fundamental physics. We still do not know if the neutrino is a Majorana or a Dirac particle, that is if the neutrino is its own antiparticle or not. Also the absolute mass scale of the neutrino is unknown, only the relative scale is known from the neutrino- oscillation experiments. These unknown features of the neutrino can be tackled by experiments trying to detect the neutrinoless double beta (0νββ) decay. The 0νββ half-life can be factorized in three terms, related to 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, mentioned above, in the frame of new physics beyond the Standard Model. For evaluation of NME several methods have been used, based on different nuclear models, like the interacting shell model (ISM), the proton-neutron quasiparticle random-phase approximation (pnQRPA), the Interacting Boson Model (IBM-2) and various mean field models among the others [1, 2, 3, 4, 5]. The presence of ambiguities in the models and the lack of strong experimental constraints correspond to significant differences in the obtained values. Using as a tool heavy-ion induced Double Charge Exchange (DCE) reactions, the NUMEN [6, 7, 8] project propose a novel way to address experimentally-driven information on the NMEs of 0νββ. A fundamental relevance for the Project has the INFN facility at Laboratori Nazionali del Sud (LNS) in Catania, made by the Superconducting Cyclotron for the acceleration of the required high resolution and low emittance heavy-ion beams and the MAGNEX large acceptance magnetic spectrometer for the detection of the ejectiles [9]. Thanks to the application of the powerful trajectory reconstruction technique [11] MAGNEX guarantees high energy, mass and angle resolutions, which established its relevance in the heavy- ion physics research [11, 12, 13, 14].

2. Heavy-Ion Double Charge Exchange and 0νββ

Heavy-ion double charge exchange reaction can proceed following different paths, going from the same initial to the same final state, among others the main are the sequential nucleon transfer mechanism, that is a fourth order process and follows the Brink's Kinematical matching conditions [15], and the meson exchange mechanism, that is a second order process.

There are some important similarities between DCE reactions and $0\nu\beta\beta$ decay, although they are mediated by different interactions. 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 $0\nu\beta\beta$ 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 $0\nu\beta\beta$ decay half-lives is not trivial and needs to be explored.

. In the 80s HI-DCE reactions were performed at energies above the Coulomb barrier in Berkeley, NSCL-MSU, IPN-Orsay and Los Alamos to determine the mass of n-rich isotopes by reaction Q-value measurements. However, due to the lack of zero-degree data and the poor yields in the measured energy spectra these experiments were not conclusive. The limitation was the very low cross sections involved, ranging from about 5-40 nb/sr [16] to 10 μb/sr [17]. Actually, this wide range of observed cross sections has never been deeply discussed. An additional complication in the interpretation of the data arose from possible contributions of multi- nucleon transfer reactions leading to the same final states [18]. Recently, DCE reactions have been explored at RIKEN and RCNP at energies between 80 and 200 MeV/u for the purpose of searching the tetra-neutron (4n) system and the DGT resonance [19, 20]. At the MAGNEX facility of the INFN-LNS we demostrate the feasibility of this kind of DCE cross sections measurements. 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. [21]. 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.

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3. NUMEN experimental campaign

. The NUMEN project is conceived in a long-range time perspective, planning to perform a comprehensive study of many candidate systems for $0\nu\beta\beta$ decay. In this frame the 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 an ^{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. We perform some long run at LNS with MAGNEX, choosing few isotopes, candidates for *0νββ,* already at our reach in terms of energy resolution and availability of thin targets.

. In this picture, 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 degree 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. The data reduction [22, 23] and analysis are almost completed and the results will be published soon.

. Systematic exploration, spanning all the variety of 0νββ decay candidate isotopes, is demanded for neutrino physics, and NUMEN is fully committed to pursue this ambitious goal. With this aim the project promotes a major upgrade of the INFN-LNS research facility in the direction of a significant increase of the beam intensity, in view of a series of experimental campaigns at high beam intensities (some pμA) and integrated charge of hundreds of mC up to C, for the experiments in which γ-coincidence measurements are required. This in turn demands challenging R&D in several aspects of the technology involved in heavy-ion collision experiments [24, 25, 26, 27]. Moreover, this project promotes and is strictly connected with a renewal of the INFN-LNS research infrastructure and with a specific R&D activity on detectors, materials and instrumentation. Moreover the acceleration of heavy-ion beams in the regime of kW power and at energies from 15 to 70 MeV/u requires a substantial change in the extraction technologies of the beam of the INFN-LNS Superconducting Cyclotron. In this frame, the development of the different theoretical aspects [28, 29, 30] connected with the nuclear structure and reaction mechanisms involved in heavy ions induced DCE reactions is a key issue for the achievement of the ambitious goals of the project. Both R&D and theoretical development are key aspects of the NUMEN project, that in perspective, aims at giving an innovative contribution in one of the most promising fields of fundamental physics, also indicating a possible growth prospect of heavy-ion physics in synergy with neutrino physics.

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