PROCEEDINGS OF SCIENCE

New results from the NUMEN project

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The idea of NUMEN project 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 ($0\nu\beta\beta$) decay. To infer the neutrino average masses from the possible measurement of the half-life of $0\nu\beta\beta$ decay, the knowledge of the nuclear matrix elements is crucial. DCE reactions and $0\nu\beta\beta$ decay present some similarities, the initial and final-state wave functions are the same and the transition operators are similar. The experimental measurements of DCE reactions induced by heavy ions present a number of challenging aspects, since they are characterized by very low cross sections.

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1. Introduction

There are still unanswered questions in neutrino physics, related to the absolute mass scale of neutrinos, to their Dirac or Majorana nature and to the number of the neutrinos species. An answer to these three questions can be obtained from neutrinos double-beta decay (DBD) and the related processes. Indeed, if observed, neutrinoless DBD may provide evidence for physics beyond the Standard Model other than the mass mechanism. Conversely, its non-observation will set stringent limits on other scenarios (sterile, ...) and on non standard mechanisms. The neutrinoless DBD half-life can be factorized in three terms, related to different physics scale: the phase-space factor, connected with Atomic physics, the Nuclear Matrix Element (NME) and a term, related to Particle physics, in which it is supposed there are the answers to the three questions, mentioned above, in the frame of new physics beyond the standard model. Several methods have been used for evaluation of NME, based on a number of nuclear models, including configuration-interaction based models like the interacting shell model (ISM) and the proton-neutron quasiparticle random-phase approximation (pnQRPA), the Interacting Boson Model (IBM-2) and various mean field models, among the others [1–6]. The presence of ambiguities in the models and the lack of strong experimental constraints correspond to significant differences in the obtained values. Moreover, possible common approximations can correspond to systematic uncertainties. A novel way to address experimentally driven information on the NMEs, has been proposed by the NUMEN [7–9] project, using as a tool heavy-ion induced Double Charge Exchange (DCE) reactions. A key aspect of the project is the use at Laboratori Nazionali del Sud (LNS) in Catania of 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 [10]. 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 [12–15]. The concurrent measurement of the other relevant reaction channels allows to isolate the direct DCE mechanism from the competing multi-nucleon transfer processes. In the NUMEN framework, an experimental campaign has started at the INFN-LNS in Catania, using the MAGNEX spectrometer, focused on DCE reactions involving the nuclei of interest for $0\nu\beta\beta$ decay.

2. Heavy-ion double charge exchange reactions and neutrinoless DBD: the NUMEN project

A Double Charge Exchange (DCE) reaction is a process induced by a projectile " a " on a target " A ", in which two protons (neutrons) of the target are converted in two neutrons (protons), being the mass number A unchanged, with opposite transition simultaneously occurring in the projectile. This reaction can proceed following different paths, among others the main are: the sequential nucleon transfer mechanism that is a fourth order process and follows the Brink's Kinematical matching conditions [16] and the meson exchange mechanism, that is a second order process. Despite DCE reactions and $0\nu\beta\beta$ decay are mediated by different interactions, there are some important similarities between them: 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 ranktwo tensor components are present, iii) a large linear momentum ($\sim$ 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. Moreover an advantage for DCE reaction is to be “accessible” in laboratory, but a simple relation between DCE cross sections and $\beta\beta$-decay half-lives is not trivial and needs to be explored. First pioneering explorations of the heavy- ion induced DCE reactions were performed in the 80s at energies above the Coulomb barrier in Berkeley, NSCL-MSU, IPN-Orsay, Los Alamos to determine the mass of n-rich isotopes by reaction Q-value measurements. However, these experiments were not conclusive mainly due to the lack of zero-degree data and the poor yields in the measured energy spectra and angular distributions. The limitation was the very low cross sections involved, ranging from about 5-40 nb/sr [17] to 10 μb/sr [18]. 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 [19]. 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 or the DGT resonance [20, 21]. Nowadays major interest has raised for DCE studies, especially because of their possible connection to $\beta\beta$-decays. In particular in ref. [22] the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction was studied at 15 MeV/u at the MAGNEX facility of the INFN-LNS, showing that high mass, angular and energy resolution energy spectra and accurate absolute cross sections are at our reach, even at very forward angles. 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 experiment demonstrated that the previous experimental limitations are almost overcome and that high resolution and statistically significant experimental data can be measured for DCE processes and that precious information towards NME determination could be at our reach. We performed first experimental investigations of the (^{20}Ne,^{20}O) DCE reaction on ^{116}Cd,^{76}Ge and ^{130}Te targets, which are candidates for the $0\nu\beta\beta$ decay. These are the first measurements of such a reaction, there are no data 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 $\sim$ 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). The total covered angular range was $0^\circ \leq \theta_{lab} \leq 8^\circ$. 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 [23, 24] and analysis are almost completed and the results will be published soon. For neutrino physics, systematic exploration, spanning all the variety of $0\nu\beta\beta$ decay candidate isotopes, is demanded 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. This in turn demands challenging R&D in several aspects of the technology involved in heavy-ion collision experiments [25–27]. 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 [28–30] connected with the nuclear structure and reaction mechanisms involved in heavy ions induced in DCE reactions is a key issue for the achievement of the ambitious goals of the project. Both RD and theoretical development are fundamental 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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