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Abstract. The NUMEN project proposes to study heavy-ion induced Double Charge Exchange (DCE) reactions with the final goal to get information on the nuclear matrix elements for neutrinoless double beta (0νββ) decay. The knowledge of the nuclear matrix elements is crucial to infer the neutrino average masses from the possible measurement of the half-life of 0νββ decay. DCE reactions and 0νββ 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.

1. Introduction

The physics of neutrinoless double beta (0νββ) decay has fundamental implications on particle physics, cosmology and fundamental physics. The observation of this rare process would signal that the total lepton number is not conserved and also it is considered one of the most promising ways to establish the Majorana or Dirac nature of neutrino and to have access to its effective mass. Therefore, this physics case is presently one of the most important researches Beyond the Standard Model and might guide the way towards a Grand Unified Theory of fundamental interactions. The 0νββ decay basically involves nuclei, thus its analysis necessarily implies nuclear structure items. Indeed, the 0νββ decay rate can be expressed as a product of three independent factors: the phase-space factor, the Nuclear Matrix Element (NME) and a term containing the effective neutrino masses. The precise knowledge of NMEs is thus mandatory to extract information on the neutrino masses, when the decay rate will be possibly measured.

The evaluation of the NMEs is presently limited to state-of-the-art model calculations based on different approaches (QRPA, shell-model, IBM etc.) [1-4]. However, the presence of ambiguities in the models and the lack of strong constraints correspond to significant differences in the obtained values. Moreover, possible common approximations can correspond to systematic uncertainties.

In order to obtain experimentally driven information on the NMEs, the NUMEN [5,6,7] and the NURE [8-9] projects are exploring the possibility of using heavy-ion induced Double Charge Exchange (DCE) reactions. Even if DCE reactions and 0νββ 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 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 advantage for DCE reaction is to be "accessible" in laboratory, but a simple relation between DCE cross sections and ββ-decay half-lives is not trivial and needs to be explored.

In this context, an experimental campaign has started at the INFN-Laboratori Nazionali del Sud in Catania using the MAGNEX large acceptance magnetic spectrometer [10] focused on DCE reactions involving the nuclei of interest for 0νββ decay. Important experimental challenges must be addressed to measure DCE reactions since they are characterized by very low cross-sections and require a high energy resolution to distinguish the transitions in the region of the ground state. Both constraints are guaranteed by the use of the MAGNEX spectrometer, a tool with high performance and flexibility. In particular, the (^{20}Ne,^{20}O) DCE reactions at 15 AMeV on ^{116}Cd, ^{76}Ge and ^{130}Te, which are nuclei candidates for the 0νββ decay, were recently measured for the first time. Some details about the experimental issues of these measurement are discussed in this paper.

2. Heavy-ion double charge exchange reactions

The experimental study of nuclear transitions where the nuclear charge is changed by two units leaving the mass number unvaried was explored in the past with the aim to obtain information on the NMEs of ββ processes. The first studies were concentrated on pion double charge exchange reactions (π^+,π^-) [11-12], which were then abandoned, due to the large differences in the momentum transfers and in the nature of the operators between them and the 0νββ decay, as reported in [13]. Some early studies of heavy-ion induced DCE reactions are also reported. They were inconclusive 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 [14] to 10 μb/sr [15]. 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 [16].

Nowadays these experimental limitations are almost overcome, as we demonstrated in the pilot experiment performed at the INFN-LNS laboratory devoted to ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar DCE reaction at 15 AMeV with the aim to measure the cross section at zero degrees [17]. The key elements in the experiment were the high resolution Superconducting Cyclotron (CS) beams and the use of MAGNEX, a modern large acceptance magnetic spectrometer characterized by high resolution in energy, mass and angle [18-19]. The high-order solution of the equation of motion is the key feature of MAGNEX, which guarantees the above mentioned performances and its relevance in the research of heavy-ion physics [20-25]. The pilot experiment demonstrated 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 [17].

3. The NUMEN and NURE projects

The aim of the NUMEN project is to measure the absolute cross section for DCE reactions on target nuclei candidates for the $0\nu\beta\beta$ decay and find a connection between the NMEs of the two processes. To move from the pilot experiment, performed on ^{40}Ca target, towards such target nuclei, important experimental limits need to be overcome. The challenge is to measure a rare nuclear transition under a very high rate of heavy ions produced by the beam-target interaction. In the exploration of nuclei of interests for $0\nu\beta\beta$ we consider that:
a) The Q-value for DCE reactions on such nuclei is typically more negative than in the case of ^{40}Ca explored in ref. [17]. This could strongly reduce the cross section.
b) The (^{18}O,^{18}Ne), which emulate the $\beta^+\beta^+$ decays, is particularly advantageous, due to the large value of the B(GT) strengths. To explore reactions of the $\beta^-\beta^-$ kind, none of the reactions looks like as favourable as the (^{18}O,^{18}Ne). For example, the (^{18}Ne,^{18}O) requires a radioactive beam, which cannot be available with comparable intensity. The proposed (^{20}Ne,^{20}O) has smaller B(GT), so a sensible reduction of the yield could be expected;
d) In some cases, gas or implanted targets are necessary, e.g. ^{136}Xe or ^{130}Xe, which are normally much thinner than solid state ones, with a consequent reduction of the collected yield;
e) In some cases the energy resolution is not enough to separate the ground from the excited states in the final nucleus. Thus, the coincident detection of γ-rays from the de-excitation of the populated states is mandatory, but at the price of the collected yield.
As a consequence, the present limits of beam power (~100 W) for the CS accelerator and acceptable rate for the MAGNEX focal plane detector (few kHz) allow us to concentrate on only few cases, which are planned in the NURE project [7-8] (e.g. ^{116}Cd, ^{130}Te, ^{76}Ge). In order to start a systematic exploration of all the nuclei of interest for $0\nu\beta\beta$ decay, an upgraded set-up, able to work with at least two orders of magnitude more luminosity than the present, is necessary. This goal can be achieved by a substantial change in the technologies implemented in the beam extraction [26], in the control of the beam induced radioactivity, in the detection of the ejectiles [27-31] and in the power dissipation of the thin targets [32]. In addition, in order to explore a wider range of incident energy, an increase of the maximum accepted magnetic rigidity is foreseen. This will be done preserving the geometry and field uniformity of the magnetic field [33-36], in order to keep the high-precision of the present trajectory reconstruction.
Finally, the development of a specific theory program to allow an accurate extraction of nuclear structure information from the measured cross sections is an important pillar of the NUMEN project. Relying on the use of the DWBA approximation for the cross section, the theory is focused on the development of microscopic models for heavy-ion DCE reactions, employing several approaches (QRPA, shell model, IBM) for inputs connected to nuclear structure quantities. We are also investigating the possible link between the theoretical description of the $0\nu\beta\beta$ decay and DCE reactions.

4. First experimental measurements on the (^{20}Ne,^{20}O) reaction

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 ~ 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 $0° \leq \theta_{lab} \leq 8°$.
Usually when a measurement is performed at zero degree, the beam enters in the spectrometer acceptance and the magnetic fields guide it to a place in the focal plane region away from the detectors. Finally it is collected by a faraday cup [17]. In the present case, the fields are set in order to transport the ^{20}Ne^{10+} ions towards the faraday cup position. However, when the beam passes through the targets a charge state distribution is originated. The maximum amount corresponds to the fully stripped ^{20}Ne^{10+} (~ 99%) but a sizeable amount of beam in the 9^+ and 8^+ charge states is also produced. These lower charge state components have a magnetic rigidity similar to that of the ejectiles of interest: ^{20}F^{9+} for the Single Charge Exchange (SCE) and ^{20}O^{8+} for DCE. Consequently, they enter in the FPD acceptance causing a limitation in beam intensity tolerable by the detector. In order to minimize the amount of ^{20}Ne^{9+} and ^{20}Ne^{8+} beams, a second target was placed downstream of the primary one to be used as a post-stripper material [37]. Different materials where tested and the final choice was a thick C foil of ~ 800 μg/cm^2. With this configuration the charge state distribution is ~ 99.1 % of 10^+, ~ $9.0 \cdot 10^{-3}$ % of 9^+ and ~ $2.0 \cdot 10^{-5}$ % of 8^+ [38]. This solution allowed only partially to reduce the background and thus a system of shields before the FPD entrance was also equipped to stop such ejectiles.
Despite these 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 SCE), in order to estimate the role of the sequential multi-nucleon transfer routes on the diagonal DCE process. The data reduction [39][40] and analysis are almost completed and the results will be published soon.

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