Challenges in double charge exchange measurements for neutrino physics

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Abstract

The neutrinoless double beta ($0\nu\beta\beta$) decay, if observed, has important implications on particle physics, cosmology and fundamental physics. In particular it can give access to the effective neutrino mass. In order to extract such information from the $0\nu\beta\beta$-decay half-life measurement, the knowledge of the Nuclear Matrix Elements (NME) is of utmost importance. In this context the NUMEN and the NURE projects aim to extract information on the NME by measuring the Double Charge Exchange (DCE) reaction cross section in selected systems of interest for the $0\nu\beta\beta$-decay. The experimental difficulties that have to be faced are the measurements at very forward-angle, the very low cross section of the process to be measured, the requirement of a high energy resolution and, eventually, the unambiguous identification of the DCE reaction from other competing processes. The large-acceptance spectrometer MAGNEX, present at INFN-LNS, Catania fulfills all the requirement above mentioned.

1 Introduction

About ninety year after the existence of neutrino has been hypothesized, the study of the property of this particle is still of crucial importance in the landscape of particle physics, cosmology and fundamental physics. In particular one of the most studied process involving neutrino particles is the $0\nu\beta\beta$-decay since, if observed, it will represent a gate through physics beyond the standard model. In fact it will sign the Majorana or Dirac character of the neutrino, it will establish if the leptonic number is conserved or not, and could give access to the neutrino effective mass.

The $0\nu\beta\beta$-decay rate can be written as product of three factors:

$$T_{0\nu}^{-1/2} = G_{0\nu}|M_{0\nu}|^2 f(m_i, U_{ei}, \xi_i)$$

where $G_{0\nu}$ is the phase space factor, $|M_{0\nu}|^2$ are the Nuclear Matrix Elements (NME) and $f(m_i, U_{ei}, \xi_i)$ is a function containing the effective mass of the neutrino that include all the physics beyond the standard model.

The issues related to such process can be separated in two classes. The first is related to the particle physics that include the function $f(m_i, U_{ei}, \xi_i)$ the second instead is related to the nuclear physics represented by the NME. In fact the $0\nu\beta\beta$-decay is, first of all, a nuclear process that occurs inside the nuclear medium. Assuming that the decay rate is known, to have access to the function $f(m_i, U_{ei}, \xi_i)$ that contains the effective mass and the physics beyond the standard model, an accurate and reliable knowledge of the NME is mandatory.

Nowadays the knowledge of the NME is mainly based on theoretical calculations that use different models as QRPA, Interacting Shell Model, IBM, Energy Density Functional Method and others [1–4]. Significant discrepancies are presently reported in literature among the different models, moreover the lack of any constrains coming from experimental data represents a major problem to extract reliable neutrino effective mass.

In order to get experimentally-driven quantitative information on NMEs the NUMEN and the NURE [5–8] projects propose to use heavy-ion induced Double Charge Exchange reactions (DCE). In DCE reactions two charge units are transfered leaving the mass number of the involved nuclei unaltered. The two processes are mediated by different interactions: the strong interaction for the DCE and the weak interaction for the $0\nu\beta\beta$-decay. Anyway there are important and strong similarity, in fact:

i the initial and the final nuclear state of the two processes are the same,

ii the operators describing the two processes are a mix of Fermi, Gamow Teller and rank-two tensor components, iii a large momentum is available in the intermediate channel.

iv they take place in the same nuclear medium.

The use of DCE reactions with the aim to obtain information on the NMEs useful for the double-β decay was investigated some decades ago. These early studies of heavy-ion induced DCE reaction was inconclusive mainly due to the lack of data at very forward angles (zero degrees) and to low statistics in the energy and angular distribution. The main limitation can be identified on the very low cross section of the DCE process [9, 10]. Furthermore additional complication in the interpretation of the data arose from the possible contribution of multinucleon transfer to the same final state of the DCE process. Today such limitations can be overcome by modern high-resolution and large-acceptance spectrometers, as the MAGNEX spectrometer [11] at INFN-LNS, Catania, a relevant instrument in the research of heavy-ion physics [12–14].

In order to study the feasibility of the proposal a pilot experiment have been performed at INFN-LNS, to measure the cross section for the reaction ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar at 270 MeV and at 0° [15]. The key tools that allowed to overcome the above-mentioned limitations were the high resolution ^{18}O beam delivered by the Superconducting Cyclotron (SC) and the large-acceptance MAGNEX spectrometer. The pilot experiment demonstrates that it is possible to measure the DCE at very forward angle (zero degree) with an high energy resolution that allow to identify the transition to the ground state and the excited states, and it it is possible to measure the other reaction mechanism competing with the DCE. Therefore high resolution and statistically significant experimental data can be measured for DCE processes and they can provide useful information for the determination of the NME for the $0\nu\beta\beta$ decay.

Even thought the DCE reaction ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar have been successfully measured, the final aim of the project is to measure the cross section for DCE reaction for systems where the target nucleus is a $0\nu\beta\beta$-decay candidate nucleus. To move toward such hot cases a number of experimental difficulties must be overcome:

i The Q-value of the DCE reactions on nuclei of interest is usually more negative than in the case of the ^{40}Ca explored in [15]. This could strongly reduce the cross section at zero degree.

ii The $(^{18}O,^{20}Ne)$ reaction, used in the pilot experiment, is particularly favorable since has a large value of the B(GT) strengths. Anyway such reaction emulate the $\beta^{+}\beta^{+}$-decay. The most of the hot cases are of the $\beta^{-}\beta^{-}$ kind, to investigate such reactions the available reaction (^{20}Ne,^{20}O) or (^{12}C,^{12}Be) have smaller B(GT), so an further reduction of the yield is expected.

iii In same case, like for the ^{130}Xe on ^{136}Xe nuclei, a gas target is required. Since gas target are usually thinner than solid target such target will suffer an additional yield reduction.

iv For same system the energy resolution of the spectrometer is not enough to disentangle the ground state from the first excited state in the final recoiling nucleus. Therefore for such cases the measurement of gamma rays is required that implies a lower yield due to the typically low efficiency of gamma detection.

In order to obtain measurements with a significant statistics the beam intensity must be substantially increased. This requires an upgrade of the experimental set-up able to work with a beam current higher of two or three orders of magnitude compared to the present value. Such upgrade requires deep changes for the accelerator, the detection system and for the target assembly.

Concerning the beam, the project requires mainly beams of carbon, oxygen and neon with intensity up to 10^{14} pps delivered to the MAGNEX spectrometer. The required energies for these beams are in the range 15-70 AMeV, which corresponds to a beam power in the range 1-10 kW to be compared with the present maximum power of about 100 W. To overcome the present limit, a stripper induced extraction, for ions with A<40, was proposed. Calculations demonstrate that such method is able to provide the required beam power [16, 17].

The main issues concerning the target are related to production of thin and very uniform target and the high heat dissipated by the beam on the target itself. The demand of a good energy resolution ($\sim$ 1/1000) requires that the targets must be thin and uniform. On the other hand, the large beam current together with the small thickness require that the generated heat inside the target be efficiently dissipated to avoid target damages. A cryogenic radiation-tolerant target system have been designed. It is based on the deposition of the target material on a thin layer of pyrolytic graphite that ensures a large heat transfer from the central region to the surrounding cold frame, thanks to the high thermal conductivity of the graphite [18, 19].

For the detection system the main upgrade foreseen are:
a) Replacement of the present focal-plane detector gas tracker.
In fact the present FPD has an intrinsic limitation in the incident-ion bearable rate of few kHz, mainly due to the fact that the multiplication is done by mean of long wires. For this reason a new gas tracker based on micro patterned technology, like GEM or THGEM is under development. This require that the electron multiplication region and the segmented readout board of the FPD tracker will be radically re-designed, at the same time new full-custom front-end and read-out electronics will be also designed [20].
b) Replacement of the silicon detector wall.
The existing stopping wall of silicon detectors is made of 50×70 mm^2, 1 mm thick silicon pad detectors and needs to be replaced in view of the higher detection rate. The new stopping wall must fulfill the requirement of energy resolution better than 1% to keep the same performances for the particle identification; a good time resolution better than 1-2 ns in order to guarantee an accurate measurement of the drift time in the gas chamber used to reconstruct the vertical track of the ejectiles; an a high granularity(modules of 1 cm^2 are in progress in SiCILIA project [21]) is required in order to limit pile-up events; the detector should be thick enough to stop the ions in a wide dynamical range of incident energies (from 10 up to 60 MeV/A) [22, 23].
c) Design of a γ-ray detectors array.
For some target ion, especially at higher energies, the energy resolution is not enough to separate the ground from the first excited state of the reaction products. An array of gamma detector (GNUMEN), with a large solid angle, will be developed with the aim to allow the discrimination of different energy states [24].

Finally the NUMEN project include inside it a theory program [25, 26]. Such theoretical developments aim at reaching a full description of the DCE reaction cross section, including also competing channels that may lead to the same final outcome, and at investigating the possible analogies with double beta decay.

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