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Experimental challenges for the measurement of the ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn double charge exchange reaction at 15 AMeV

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Abstract. The knowledge of the nuclear matrix elements (NME) entering in the expression of the half-life of the neutrinoless double beta decay is fundamental for neutrino physics. Information on the nuclear matrix elements can be obtained by measuring the absolute cross section of double charge exchange nuclear reactions. The two processes present some similarities, the initial and final-state wave functions are the same and the transition operators are similar. The experimental measurements of double charge exchange reactions induced by heavy ions present a number of challenging aspects, since such reactions are characterized by very low cross sections. Such difficulties are discussed for the measurement of the ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn reaction at 15 AMeV.

1. Introduction

The physics of neutrinoless double beta (0νββ) decay has fundamental implications on particle physics, cosmology and fundamental physics. In particular it is considered one of the most promising ways to probe the Majorana or Dirac nature of neutrino and to have access to its effective mass. Furthermore, the observation of 0νββ would signal that the total lepton number is not conserved. For these and other fundamental implications, 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

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fundamental interactions. Since the 0νββ decay process involves nuclei, its analysis necessarily implies nuclear structure items. 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. Thus, even if the decay rate will be measured, the knowledge of the NME is mandatory to extract information on the neutrino masses.
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, significant differences in the obtained values are still found, due to the ambiguities in the models and the lack of strong constraints. Moreover, possible common approximations can correspond to systematic uncertainties.
The possibility of using heavy-ion induced Double Charge Exchange (DCE) reactions as tools to have experimentally driven information on the NMEs is at the basis of the NUMEN [5,6] and the NURE [7-8] projects. Despite the two processes 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 description of NMEs extracted from DCE and 0νββ presents the same degree of complexity, with the advantage for DCE to be "accessible" in laboratory. However 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 [9] focused on DCE reactions involving the nuclei of interest for 0νββ decay. These reactions represent an important experimental challenge 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 ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn DCE reaction at 15 AMeV was recently measured for the first time. Some details about the experimental issues of this measurement are discussed in this paper.

2. Heavy-ion double charge exchange reactions

Due to the possibility to obtain information on the NMEs of ββ processes, 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. A large effort was done to study pion double charge exchange reactions (π^+,π^-) [10-11]. A factorization of the cross section in terms of a nuclear structure part, which is related to the nuclear matrix element, and a reaction part has been deduced in these cases [12-13]. However, suggestions that pion double charge exchange might be used to probe 0νββ decay NMEs were abandoned, due to the large differences in the momentum transfers and in the nature of the operators, as reported in [14]. Early studies of heavy-ion induced DCE reactions were also inconclusive. The reason was the lack of zero-degree data and the poor yields in the measured energy spectra and angular distributions, due to the very low cross sections involved, ranging from about 5–40 nb/sr [15] to 10 μb/sr [16]. Actually, this wide range of observed cross sections has never been deeply discussed. An additional complication in the interpretation of the data was due to possible contributions of multi-nucleon transfer reactions leading to the same final states [17].
Nowadays these experimental limitations are almost overcome, as we demonstrated in a pioneering experiment performed at the INFN-LNS laboratory. In particular, we studied the DCE reaction ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar at 15 AMeV, with the aim to measure the cross section at zero degrees [18]. The key elements in the experiment were the high resolution Superconducting Cyclotron (CS) beams and the use of MAGNEX, a modern high resolution and large acceptance magnetic spectrometer characterized by high resolution in energy, mass and angle [19-20]. 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 [21-25]. In this experiment we

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have shown 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.

3. The NUMEN and NURE projects

To move towards nuclei candidates for $0\nu\beta\beta$ decay 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. The exploration of nuclei of interests for $0\nu\beta\beta$ is particularly stimulating as well as challenging. We consider that:

a) The Q-value for DCE reactions on nuclei of interest for 0νββ is normally more negative than in the case of ^{40}Ca explored in ref. [18]. This could strongly reduce the cross section at very forward angles.

b) The (^{18}O,^{18}Ne) reaction is particularly advantageous, due to the large value of the B(GT) strengths. However, this reaction is of $\beta^+\beta^+$ kind, while most of the research on 0νββ is in the opposite side. None of the reactions of $\beta^-\beta^-$ kind 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 is 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 (about half MeV) 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 [27-30] and in the power dissipation of the thin targets [31]. In addition, the project demands for an enhancement of the maximum accepted magnetic rigidity, preserving the geometry and field uniformity of the magnetic field [32-35] 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 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 0νββ decay and DCE reactions.

4. First experimental measurements on the ^{20}Ne + ^{116}Cd system

We performed the first experimental investigation of the (^{20}Ne,^{20}O) DCE reaction on a ^{116}Cd target, which is a candidate for the 0νββ decay. This is the first measurement 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 a ^{116}Cd rolled target of 1370 $\mu g/cm^2$ thickness. The thickness was carefully chosen in order to obtain an energy resolution which allows to distinguish the transition to the residual ^{116}Sn ground state from its first excited state at 1.293 MeV. 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 and it is guided by the magnetic fields to a place in the focal plane region away from the detectors and finally collected by a faraday cup [18]. The fields are thus set in order to transport the $^{20}Ne^{10+}$ ions towards the faraday cup position. However, when the beam passes through the ^{116}Cd target 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 the detector tolerable rate. For this reason, a second target was placed downstream of the ^{116}Cd to be used as a post-stripper material in order to minimize the amount of $^{20}Ne^{9+}$ and $^{20}Ne^{8+}$ beams. Different materials where tested and the final choice was a thick C foil of 987 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^+ [36]. 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 single charge exchange), in order to estimate the role of the sequential multi-nucleon transfer routes on the diagonal DCE process. The data reduction and analysis are almost completed and the results will be published soon.

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