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Experimental challenges in the measurement of double charge exchange reactions within the NUMEN project

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Abstract. The NUMEN project proposes to measure the absolute cross sections of heavy-ion induced Double Charge Exchange (DCE) reactions with the final goal to get information on the nuclear matrix elements involved in the neutrinoless double beta $(0\nu\beta\beta)$ 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 $0\nu\beta\beta$ decay and also to compare experiments on different isotopes. 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. Many challenges have to be faced for the experimental measurements of DCE reactions induced by heavy ions, since they are characterized by very low cross sections.

1. Introduction

The physics of neutrinoless double beta $(0\nu\beta\beta)$ decay has fundamental implications since its observation would signal that the total lepton number is not conserved and also it would establish the Majorana nature of neutrino. Therefore, the search of this very rare process is the topic of many



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research facilities all over the world. The $0\nu\beta\beta$ decay basically involves nuclei, thus its analysis necessarily implies nuclear structure items. Indeed, the $0\nu\beta\beta$ decay rate can be expressed as a product of three independent factors: the phase-space factor, the Nuclear Matrix Element (NME) and a term which - in the standard scenario of decay mediated by the exchange of Majorana neutrinos – contains 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. It is also a critical ingredient to convert the actual limits on the half-life established by the experiments with different isotopes into limits on the neutrino mass.

Presently, the evaluation of the NMEs is based mainly on state-of-the-art calculations with different approaches (QRPA, shell-model, IBM etc.) [1-4]. However, significant differences in the obtained values are present due to ambiguities in the models and the lack of strong constraints. Moreover, possible common approximations could correspond to systematic uncertainties.

In order to give experimentally driven information on the NMEs, the NUMEN [5-7] and the NURE [8-9] projects started an experimental campaign on heavy-ion induced Double Charge Exchange (DCE) reactions. Even if DCE reactions and $0\nu\beta\beta$ decay are mediated by different interactions, there is a link between them based on some important similarities: 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 is that DCE reactions can be induced in laboratory, but a simple relation between DCE cross sections and $\beta\beta$ -decay half-lives is not trivial and needs to be explored.

The experimental activity of the projects is mainly performed at the INFN-Laboratori Nazionali del Sud in Catania using the high resolution Superconducting Cyclotron (CS) beams and the MAGNEX large acceptance magnetic spectrometer, which is characterized by high resolution in energy, mass and angle [10-12]. Indeed, the high-order solution of the equation of motion implemented in MAGNEX guarantees the above mentioned performances and its relevance in the research of heavy-ion physics [13-17], some of them obtained from its coupling to the EDEN neutron detector array [18][19].

We already established the feasibility of such experiments by studying the ⁴⁰Ca(¹⁸O, ¹⁸Ne)⁴⁰Ar DCE reaction at 15 AMeV with the aim to measure the absolute cross section at zero degree [20]. This 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 [20].

Recently, we focused the experimental activity on DCE reactions involving the nuclei of interest for $0\nu\beta\beta$ decay. In particular, the (²⁰Ne,²⁰O) DCE reactions at 15 AMeV on ¹¹⁶Cd, ⁷⁶Ge and ¹³⁰Te, were measured for the first time. Some details about the experimental challenges and data reduction procedure of these measurements are discussed in this paper.

2. Towards the experiments of 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. With respect to the pilot experiment, performed on ⁴⁰Ca target, DCE reactions on such target nuclei are characterized by some additional experimental difficulties. 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. [20]. This could strongly reduce the cross section.

b) The (¹⁸O, ¹⁸Ne), 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, a possible candidate is, for example, the (¹⁸Ne, ¹⁸O), which requires a radioactive beam that cannot be available with comparable intensity. The proposed (²⁰Ne, ²⁰O) has smaller B(GT), so a sensible reduction of the yield could be expected;

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d) The study of some nuclei requires gas or implanted targets, e.g. ¹³⁶Xe or ¹³⁰Xe, which are normally much thinner than solid state ones, with a consequent reduction of the collected yield;

e) In some cases the achievable 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 [8-9] (e.g. ¹¹⁶Cd, ¹³⁰Te, ⁷⁶Ge).

In order to start a systematic exploration of all the nuclei of interest for $0\nu\beta\beta$ decay, we need to work at about two orders of magnitude more luminosity than the present and thus an upgraded set-up is necessary. The plan is to develop a substantial change in the technologies implemented in the beam extraction [21], in the control of the beam induced radioactivity, in the detection system of MAGNEX [22-26] and in the power dissipation of the thin targets [27]. 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 [28-31], 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 mandatory and is part of the NUMEN project.

3. First experimental measurements on the (²⁰Ne,²⁰O) reaction

We performed first experimental investigations of the (²⁰Ne,²⁰O) DCE reaction on ¹¹⁶Cd,⁷⁶Ge and ¹³⁰Te targets, which are nuclei 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 ²⁰Ne¹⁰⁺ beam was accelerated at 15 AMeV by the CS of INFN-LNS. The thicknesses of the targets were 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. A ¹¹⁶Cd rolled target of 1370 µg/cm² thickness and ⁷⁶Ge (386 µg/cm² thickness) and ¹³⁰Te (247 µg/cm² thickness) both evaporated on a C backing of ~ 50 µg/cm² were used. The thickness of ¹¹⁶Cd is much higher than that of ⁷⁶Ge and ¹³⁰Te, because the first excited state in the corresponding residual nucleus of ¹¹⁶Sn is at 1.293 MeV, to be compared to 0.559 MeV in ⁷⁶Se and 0.536 MeV in ¹³⁰Xe. The MAGNEX spectrometer was placed at forward angles including zero degree in the full acceptance mode (~50 msr).

The magnetic fields were set in order to transport the ²⁰Ne¹⁰⁺ ions towards the faraday cup position at the focal plane. However, when the beam passes through the targets a charge state distribution is originated. The maximum amount corresponds to the fully stripped ²⁰Ne¹⁰⁺ (~ 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: ²⁰F⁹⁺ for the Single Charge Exchange (SCE) and ²⁰O⁸⁺ 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 ²⁰Ne⁹⁺ and ²⁰Ne⁸⁺ beams, a second target was placed downstream of the primary one to be used as a post-stripper material. Different materials where tested and the final choice was a thick C foil of ~ 800 µg/cm². With this configuration the charge state distribution is ~ 99.1 % of 10⁺, ~ 9.0 · 10⁻³ % of 9⁺ and ~ 2.0 · 10⁻⁵ % of 8⁺ [32]. 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.

4. Data reduction

The data reduction procedure presents some challenges due to the identification of heavy ejectiles and the correction of the high-order aberrations through the ray-reconstruction procedure for the much suppressed DCE reaction channel. The ejectiles are identified in atomic number (Z), mass number (A)

and charge state (q) according to the technique described in refs. [33-34, which provides mass resolution as high as 1/160.

The ray-reconstruction procedure is then applied to the identified set of data, in order to extract the momentum vector at the reaction point of the ejectiles and the absolute cross section. In order to perform an accurate trajectory reconstruction of the measured data, a precise model of the spectrometer response in the specific magnetic setup of the experiment is necessary. The way to test the accuracy of such a model comes from a comparison between the measured phase space parameters at the focal plane and the simulated events for the selected reaction [35].

Once a reliable direct transport map has been obtained, it can be inverted and applied to the measured final coordinates in order to obtain the initial phase space parameters at the target point. These are directly related to the modulus of the ejectile momentum and the scattering angle. Indeed, from the initial vertical ϕ_i and horizontal θ_i angles, the laboratory scattering angle θ_{lab} is extracted. Then, from the reconstructed momentum, the initial kinetic energy of the ejectiles is deduced. The corresponding Q-values, or equivalently the excitation energy $E_x = Q - Q_0$, where Q_0 is the ground state to ground state Q-value, are finally obtained by a missing mass calculation based on relativistic energy and momentum conservation laws, assuming a binary reaction.

An example of the correlation plot θ_{lab} versus E_x is shown in Figure 1 for the ¹¹⁶Cd(²⁰Ne,²⁰O)¹¹⁶Sn DCE reaction in the angular range 3° < θ_{lab} < 14°. The ¹¹⁶Sn ground state region is visible as vertical and straight locus around $E_x = 0$, even with the low collected yield, as expected since the E_x parameter does not depend on the scattering angle for transitions to the ¹¹⁶Sn states. The efficiency cut on the bottom of the distribution is due to the presence of the protection screen that limit the FPD acceptance.



Figure 1 Plot of the reconstructed θ_{lab} versus the ¹¹⁶Sn excitation energy (E_x) for the ¹¹⁶Cd(²⁰Ne,²⁰O)¹¹⁶Sn reaction at 15 AMeV.

A major achievement of the ray reconstruction technique is the very small systematic error obtained in the horizontal θ_i (-0.01° ± 0.04°) and vertical ϕ_i (-0.05° ± 0.3°) angles, as demonstrated in Ref. [36]. In addition a high resolution is also obtained in θ_i (0.2°) and ϕ_i (0.7°) angles. Regarding the reconstructed momentum modulus, a resolution of 1/1800 with an accuracy better than 1/1600 is obtained for the reaction channels of interest.

When dealing with very rare processes, as the DCE reactions, other important parameters of the experimental measurement are the cross section sensitivity and the rejection factor. In particular, looking at the reconstructed θ_{lab} versus E_x plot shown in Figure 1, we can see that there are no spurious counts in the region between -7 and -2 MeV. This corresponds to sensitivity better than 1 count within 5 σ confidence level in an energy range of 1 MeV. To estimate the rejection factor in the region of

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interest for the transition ¹¹⁶Cd(²⁰Ne,²⁰O)¹¹⁶Sn_{g.s.}, we estimated the total ejectile flux emerging from the target seen by the solid angle aperture of the spectrometer according to the formula: $N_{reac}^{tot} = N_{targ}N_{beam}\sigma_{reac}\Delta\Omega_{MAGNEX}^{\varepsilon}/4\pi$. The use of this formula requires the knowledge of: the number of ions/cm² deduced from the target thickness (N_{targ}), the number of incident ions measured by the Faraday Cup (N_{beam}), the solid angle seen by MAGNEX taking into account the transport efficiency of the specific setup (in the present case $\Delta\Omega_{MAGNEX}^{\varepsilon} \sim 0.041$ sr) [37] and the total reaction cross section σ_{reac} for the system ²⁰Ne + ¹¹⁶Cd ($\sigma_{reac} \cong \pi R^2 \sim 1.8$ b). After the $B\rho$ selection by the dipole magnetic field, the particle identification and the ray-reconstruction technique, we are able to obtain a tiny amount of spurious counts in the DCE region of interest (< 0.25) that corresponds to a rejection factor better than 4×10^{-9} in the region of interest.

5. Conclusions

The results described in this paper confirm MAGNEX as the ideal instrument for the challenging measurement of heavy-ion induced DCE reactions. Despite the experimental limitations, it allows to measure energy spectra and absolute cross sections for the DCE reaction channel at very forward angles including zero degree.

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 and analysis are almost completed and the results will be published soon.

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