USING DOUBLE CHARGE EXCHANGE REACTIONS TOWARDS $0\nu\beta\beta$ NUCLEAR MATRIX ELEMENTS*

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The knowledge of the nuclear matrix elements (NME) for the neutrinoless double beta decay is fundamental for neutrino physics. The NMEs indeed enter in the expression connecting the half-life of the neutrinoless double beta decay to the neutrino mass. Information on the nuclear matrix elements can be obtained by measuring the cross section of double charge exchange nuclear reactions. The basic point is that the initial and final-state wave functions in the two processes are the same and the transition operators are similar. The double charge exchange cross sections can be factorized in a nuclear structure term containing the matrix elements and a nuclear reaction factor. First pioneering experimental results for the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction at 270 MeV incident energy show that such cross section factorization reasonably holds for the 0^+ to 0^+ transition to the $^{40}\mathrm{Ar_{gs}}$, at least at very forward angles.

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1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is considered one of the best ways to probe the Majorana or Dirac nature of neutrino and to extract its effective mass. Moreover, if observed, $0\nu\beta\beta$ would signal that the total lepton number is not conserved. Presently, this physics case is one of the most important researches Beyond the Standard Model and might guide the way towards a Grand Unified Theory of fundamental interactions.

Since the $\beta\beta$ decay process involves nuclei, its analysis necessarily implies nuclear structure items. The $\beta\beta$ decay rate can be expressed as a product of independent factors: the phase-space factors, the nuclear matrix elements

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(NME) and a function of the masses of the neutrino species. Thus, the knowledge of the NME can give information on the neutrino mass, if the $\beta\beta$ decay rate is measured.

A new project is starting at INFN — LNS (Italy) with the aim of using, for the first time, nuclear reactions of double charge-exchange (DCE) as a tool to extract the $\beta\beta$ NME. In both DCE reactions and $\beta\beta$ decay, the initial and final nuclear states are the same and the transition operators have the same spin–isospin structure. Thus, even if the two processes are mediated by different interactions, the NME are connected and the determination of the DCE cross sections can give crucial information on $\beta\beta$ matrix elements.

One should remind that a similar link is well-established at a level of few percent between single β decay strengths and single charge-exchange reaction cross sections, under specific dynamical conditions. Indeed, single charge-exchange reactions are routinely used as a tool to determine Fermi and Gamow–Teller transition strengths for single β decay, as demonstrated by several papers and reports [1]. However, no one has ever tested this proportionality between $\beta\beta$ decay and DCE strength till now. The direct access to the nuclear matrix elements has been until now hindered by experimental difficulties mainly due to the extremely low probability of the nuclear transitions.

As a consequence, presently, the evaluation of the matrix elements is only limited to calculations on the basis of different methods (QRPA, shell-model, IBM, *etc.*) [2–5]. Cooperative efforts for the determination of $\beta\beta$ matrix elements are encouraged by the international neutrino community, with a special emphasis to provide relevant experimental information.

2. Earlier DCE studies

The experimental study of other nuclear transitions where the nuclear charge is changed by two units leaving the mass number unvaried, in analogy to the $\beta\beta$ decay, could give important information.

A large effort has been done in the past years to study pion double charge exchange reactions (π^+, π^-) even with the aim to extract information on nuclear matrix elements for $\beta\beta$ decay [6–8] with the result that the double charge exchange of pions in flight between two nucleons can give a substantial contribution to neutrinoless nuclear $\beta\beta$ decay under certain conditions. 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 that cases [9, 10]. However, suggestions that pion double charge exchange might be used to probe $0\nu\beta\beta$ decay NMEs were abandoned, due to the large differences in the momentum transfers and in the nature of the operators, as reported in [11].

Early studies of heavy-ion induced double charge exchange reactions (DCE) 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 [12, 13] to 10 μb/sr [14]. 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 [15, 16].

3. The first experiment: ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar

A pilot experiment has been performed at INFN — LNS to test the feasibility of such kind of reactions with the aim of extracting information on NME. In such an experiment, the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar DCE reaction was studied together with the competing processes: single charge-exchange ^{40}Ca(^{18}O,^{18}F)^{40}K, two-proton ^{40}Ca(^{18}O,^{20}Ne)^{38}Ar and two-neutron ^{40}Ca (^{18}O,^{16}O)^{42}Ca transfer.

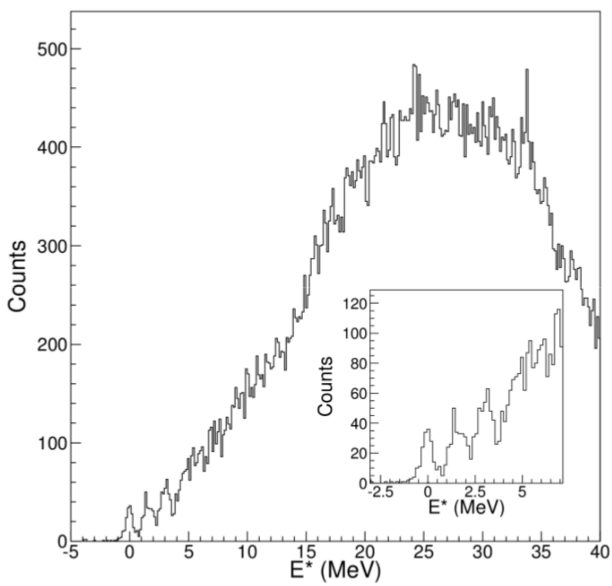

Fig. 1. Excitation energy spectrum of ^{40}Ar populated by the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar DCE reaction at 270 MeV. In the insert, a zoomed view of the low excitation energy region is shown.

The ejectiles produced in the collisions were momentum-analyzed by the MAGNEX large acceptance spectrometer [17–20] and detected by its focal plane detector [21, 22]. An angular range of $-1.2° < \theta_{\rm lab} < +8°$ in the laboratory frame was explored. The ejectiles identification was achieved as described in Ref. [23]. The positions and angles of the selected ions measured at the focal plane were used as input for a 10^{th} order ray-reconstruction of the scattering angle θ_{lab} and excitation energy $E_x = Q_0 - Q$ (where Q_0 is the ground-to-ground state reaction Q-value) [24, 25]. Figure 1 shows the measured energy spectrum for the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar DCE reaction.

In the DCE energy spectrum, the ^{40}Ar ground state is clearly separated from the not resolved doublet of states ^{40}Ar 2^+ at 1.460 MeV and ^{18}Ne 2^+ at 1.887 MeV. At higher excitation energy, the measured yield is spread over many overlapping states.

4. Cross section analysis

Assuming the validity of the proportionality relation between DCE cross-section and NME, in analogy to single β decay, the NME for the transition $^{40}\text{Ca}_{\text{gs}}$ to $^{40}\text{Ar}_{\text{gs}}$ has been extracted. More details on the approximations used to extract the numbers have been published in Ref. [26]. Under the hypothesis that the considered transition is pure GT, the extracted NME results $M^{\text{DCE}}(\text{GT}) = 0.42 \pm 0.21$. Analogously, in the case of pure Fermi process, we extract $M^{\text{DCE}}(\text{F}) = 0.28 \pm 0.14$. The systematic error is about $\pm 50\%$, estimated by checking the sensitivity of the results to the used parameters. It mainly comes from the uncertainty on volume integrals of the effective two-body interaction. The contribution of the experimental error ($\pm 10\%$ systematic, $\pm 25\%$ statistical) is less relevant in this case. We notice that the NME in the case of pure Fermi or pure GT transitions are very similar so even the weighted average, representing a more realistic combination of both contribution, will be. Assuming the known GT and F strengths from literature, we can get an estimate of the weights and we could infer the matrix element for the $0\nu\beta\beta$ decay of ^{40}Ca: $M^{\text{DCE}}(^{40}\text{Ca}) = 0.37 \pm 0.18$.

To speculate, a comparison between the present result for ^{40}Ca and the NME of $0\nu\beta\beta$ decay of ^{48}Ca can be done assuming pure F and GT and artificially removing the effect of the Pauli blocking, since the same single particle shells are involved but no Pauli blocking is active in the ^{48}Ca case. In ^{40}Ca, indeed, the transitions take place only through the small $1f_{7/2}$, $1f_{5/2}$ particle and $1d_{3/2}$ hole components of the $^{40}\text{Ca}_{\text{gs}}$ wave function, which account for about 14% of the total. So, it is possible to approximately deduce the $^{48}\text{Ca}_{\text{gs}}$ NME by just multiplying the ^{40}Ca NME by a factor of 7, obtaining $M^{\text{DCE}}(^{40}\text{Ca}) = 2.6 \pm 1.3$. It is noteworthy that this number is compatible with literature for the state-of-the-art calculations of the ^{48}Ca $0\nu\beta\beta$ NMEs [4, 27].

5. Towards the NUMEN project

High resolution and statistically significant experimental data on heavy-ion double charge exchange reactions in a wide range of transferred momenta have been measured. The availability of the MAGNEX spectrometer for high resolution measurements of very suppressed reaction channels was essential for such a pioneering measurement.

Nuclear matrix elements are extracted under the hypothesis of a two-step charge exchange process. Despite the approximations used in our model, which determine an uncertainty of $\pm 50\%$, the present results are compatible with the values known from literature, signaling that the main physics content has been kept. The DCE unit cross section is likely to be a predictable quantity, in analogy to the single charge exchange processes.

This makes the (^{18}O,^{18}Ne) reaction very interesting to investigate the DCE response of the nuclei involved in $0\nu\beta\beta$ research. A deeper investigation of DCE reactions is worthwhile in the future and is one of the main aims of a new project which is starting at INFN — LNS, the NUMEN project. Other target nuclei which are candidates for the $0\nu\beta\beta$ will be used and different bombarding energies will be studied in order to explore the systematic behavior. In all cases, the contextual measurements of the multi-nucleon transfer and single charge exchange channels is mandatory.

Studying if the unit cross section is a smooth and thus controllable function of the target mass and the incident energy is the first and most ambitious goal of the NUMEN project. If achieved, this result will provide an experimental approach to $0\nu\beta\beta$ decay nuclear matrix elements. This corresponds to verify the above mentioned factorization and gives an accurate description of the reaction mechanism. The development of a consistent microscopic description of the heavy-ion double charge exchange reaction and the nuclear structure part is essential for this purpose. The use of the quantum approach for the DWBA or CRC cross section with form factors including QRPA transition densities (as well as Shell Model or IBM densities) is a suitable framework in which this theory can be developed. Experimentally, the achievement of the first goal requires that a systematic set of appropriate data is built, facing the relative experimental challenges connected with the low cross sections and high resolutions requests.

In addition, the project has two more goals. The measured DCE absolute cross sections provide a powerful tool for tuning the nuclear structure theory. The matrix elements for double charge exchange and neutrino-less double beta decay probe the same initial and final wave functions by operators with similar structure. Consequently, the measured DCE absolute cross sections allow to test the goodness of the assumptions done for the unavoidable truncation of the many-body wave functions. The reaction part needs to be precisely controlled to this purpose, a result that is at reach within a fully quantum scattering framework. Once the nuclear wave functions have been tested by DCE cross sections, the same can be used for $0\nu\beta\beta$ decay nuclear matrix elements. Promoting the development of these kind of constrained theories for the NME of the $0\nu\beta\beta$ decay is thus an important goal that NUMEN can achieve even with a reduced experimental dataset and without assuming cross section factorization.

Finally, the third goal is to provide relative NME information on the nuclei candidate for $0\nu\beta\beta$ decay. In the case of validity of cross section factorization, the ratio of measured cross sections can give a model-independent way to compare the sensitivity of different half-life experiments. This result can be achieved even in presence of sizable systematic errors in the measured cross sections and in the extraction of unit cross sections, as they are largely reduced in the ratio. Performing these comparative analyses could strongly impact the future developments of the field, especially in a scenario where fundamental choices for the best isotope candidates for $0\nu\beta\beta$ decay need to be done.

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