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Double charge-exchange reactions for the nuclear matrix elements of neutrinoless double beta decay

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Abstract. Double charge exchange (DCE) reactions induced by heavy ions are crucial tools to access information relevant for neutrinoless double beta decay nuclear matrix elements. In this context the NUMEN project aims to investigate, for each system of interest, the DCE reaction channel together with the whole set of reactions promoted by the same projectile/target interaction in the same experimental conditions and within the same theoretical framework.

1. Introduction

The NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project [1, 2, 3, 4] proposes to use heavy-ion induced Double Charge Exchange reactions (HI-DCE) as a tool to access quantitative information, relevant for $0\nu\beta\beta$ decay nuclear matrix elements (NME). A critical aspect of $0\nu\beta\beta$ is that the associated NME must be known with high accuracy to obtain information on the term beyond-standard-model, connected with the neutrino absolute mass. The intrinsic many-body nature of the involved states of the parent and daughter nuclei makes this task particularly challenging. A comparison of the results of NME calculations, obtained within various nuclear structure models, indicates that significant differences are found, which makes the present situation not satisfactory [5].

The HI-DCE reactions used in NUMEN are characterized by the transfer of two units of charge, leaving the mass number unchanged, analogously to the $0\nu\beta\beta$ decays. The key similarities between $0\nu\beta\beta$ and HI-DCE are that initial and final nuclear states are the same and the transition operators in both cases contain a superposition of isospin, spin-isospin and rank-two tensor components with a relevant available momentum (100 MeV/c). In addition to the HI-DCE, NUMEN aims at the exploration of all the relevant reaction channels promoted by the projectile/target interaction. They include elastic and inelastic scattering, single and double nucleon transfer reactions and single charge exchange reactions. Such an approach has been defined as a "multi-channel approach" [6, 7, 8, 9, 10, 11, 12].

The NURE/NUMEN experimental campaigns [13], conducted so far at INFN-LNS, using the K800 Superconducting Cyclotron to accelerate beams and the MAGNEX large acceptance magnetic spectrometer [14, 15, 16, 9] for the detection of the ejectiles have brought to first results, giving encouraging indication on the capability of the proposed technique to access relevant quantitative information.

NUMEN is conceived in a long-range time perspective, in the view of a comprehensive study of many candidate systems for $0\nu\beta\beta$ decay. Moreover, the project has promoted a renewal of the INFN-LNS research infrastructure and a specific R&D activity on detectors, materials and instrumentation [3, 17, 18, 19].

2. The HI-DCE reaction

First attempts to explore DCE reactions date back to the late Seventies. Pioneering experiments were performed on HI-DCE reactions, such as (^{18}O,^{18}Ne), (^{14}C,^{14}O), (^{18}O,^{18}C) as well as pion-induced reactions (π^+,π^-) and (π^-,π^+) [20, 21, 22, 23, 24, 25]. The main purpose was to populate nuclei far from stability extracting their mass excess from reaction Q-value measurements.

In the recent years, HI-DCE studies have raised major interest especially because of their possible connection to $0\nu\beta\beta$ decay. Important results have been achieved by the (^{18}O,^{18}Ne) reaction at the INFN-LNS laboratory in Catania, using a ^{18}O beam from the K800 superconducting cyclotron accelerator and momentum-analysing the reaction products by the MAGNEX magnetic spectrometer [14]. In particular, in Ref. [26], pioneering experimental results for the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction at 15 MeV/u incident energy were reported. An angular range corresponding to scattering angles in the centre of mass $0^\circ < \theta_{CM} < 12^\circ$ was explored. Thanks to the use of a powerful ray-reconstruction technique [27, 28, 29, 30], high-resolution energy spectra and angular distributions were extracted. In the obtained DCE energy spectrum, shown in Fig. 1, the ^{40}Ar ground state is clearly separated from the not resolved doublet of 2^+ states of ^{40}Ar at 1.460 MeV and ^{18}Ne at 1.887 MeV. At higher excitation energy the measured yield is spread over many overlapping states and the cross section tends to increase with excitation energy.

The work of Ref. [26] shows for the first time high resolution and statistically significant experimental data on HI-DCE reactions in a wide range of transferred momenta. The measured cross section angular distribution (reported in Fig.1) shows an oscillating pattern, that has been described in Ref. [26] by an $L = 0$ Bessel function. Furthermore in the same reference, the cross section is factorized for the first time adopting a schematic two-step reaction mechanism with realistic isovector interaction and Fermi and GT strength in the intermediate channel. A reasonable NME is extracted for the crucial $0^+ \rightarrow 0^+$ DCE transition to ^{40}Ar$_{gs}$. This makes the (^{18}O,^{18}Ne) reaction very promising to investigate the DCE response of the nuclei involved in $0\nu\beta\beta$ research.

Another new HI-DCE reaction, the (^{20}Ne,^{20}O), has been introduced for the first time at

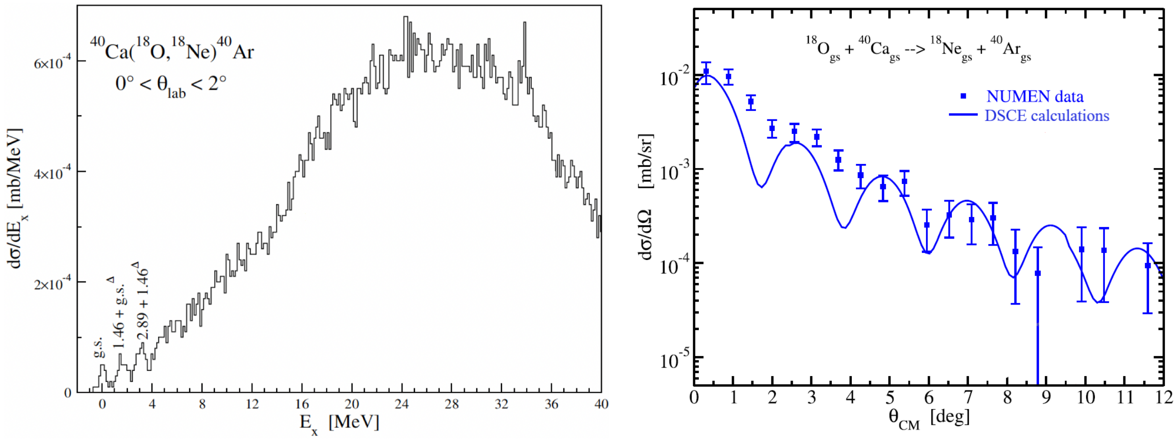

Figure 1. (left) Excitation energy spectrum for the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction at 15 MeV/u [26]. (right) Differential cross section of the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$_{gs}$ transition as a function of θ_{CM} and q. The curve is the result of the DSCE mechanism calculations as described in Ref. [31].

INFN-LNS, with the aim to probe $\beta^-\beta^-$ like nuclear response. The ^{130}Te(^{20}Ne,^{20}O)^{130}Xe reaction was measured at 15 MeV/u at very forward angles with the MAGNEX spectrometer [32]. The interest in the ^{130}Te system is related to the fact that it is one of the candidates for $0\nu\beta\beta$ [33]. The excitation energy spectrum is presented in Fig. 2. Only a few events were detected in the ground state region. The best estimate for the integrated DCE cross section is 13 nb in the angular range $0° < \theta_{lab} < 9.5°$ and in the energy range -1 MeV $< E_x <$ 1 MeV [32]. This measurement provides, for the first time, the estimation of the order of magnitude of the extremely low DCE cross section for the transition under study. The upgrade of the INFN-LNS superconducting cyclotron and of the MAGNEX FPD is now in progress [4, 17, 18, 19], giving the opportunity for a future deeper exploration of this reaction with a much higher beam current and consequently with better statistics.

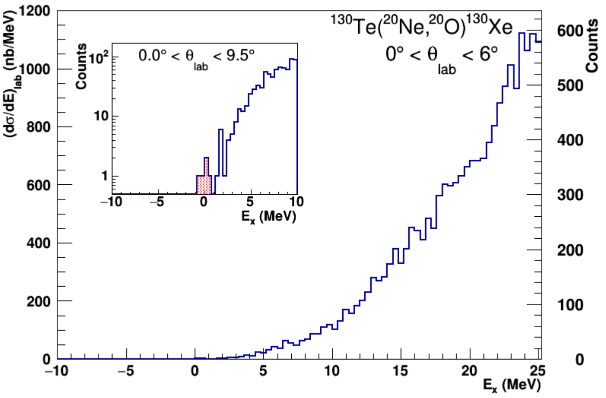

Figure 2. Excitation energy spectrum for the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction at 15 MeV/u incident energy and $0° < \theta_{lab} < 6°$. Inset: zoomed view for $E_x < 10$ MeV and full angular range $0° < \theta_{lab} < 9.5°$ with the vertical axis in logarithmic scale. From Ref. [32].

A parallel activity searching for the most promising probes for double charge exchange reactions has been carried out in the recent years at RCNP and RIKEN laboratories in Japan. New reactions have been considered, such as the (^{8}He,^{8}Be), the (^{11}B,^{11}Li) and the (^{12}C,^{12}Be), demonstrating a suitable toolbox of complementary reactions for forthcoming DCE studies.

A microscopic theory of DCE based on semi-classical eikonal approximation was developed in Ref. [34] showing that the DCE differential cross sections can be factorized as the product of reaction and structure parts in closure approximation and in the low-momentum-transfer limit, corresponding to very forward detection angles, and that a further factorization in terms of target and projectile NMEs can be performed.

However, the description of the complete nuclear reaction mechanism of HI-DCE needs a formulation based on quantum-mechanical microscopic reaction theory which accounts for the possible competition of different processes feeding the DCE channel. Indeed, HI-DCE can proceed either via multi-nucleon transfer (TDCE), mediated by mean-field, or through the exchange of correlated or uncorrelated mesons.

The TDCE mechanism can be described within distorted wave Born approximation (DWBA) or coupled channels methods. However, the practical implementation of a sufficiently complete calculation has not been possible until very recent times [35], due to the fact that at least fourth-order nucleon transfer scheme is required. The study reported in Ref. [35] shows that the TDCE cross section is orders of magnitude lower than the DCE measured cross section, at least in the explored experimental conditions.

For the meson exchange mechanisms, the theoretical framework formerly introduced for single charge exchange in Ref. [36], has been recently extended to second order [31, 37], describing the successive exchange of two uncorrelated charged mesons. This formalism reveals a remarkable similarity of DSCE with $2\nu\beta\beta$ decay, although a much richer multipole spectrum is accessed in HI-DCE. The result of the application of such a DSCE approach to the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar data is described in details in Refs. [31, 37] and shown also in Fig. 1.

A completely new reaction mechanism, named Majorana mechanism (MDCE), has been recently introduced in Refs. [38, 39]. The MDCE mechanism relies on neutral mesons induced nucleon-nucleon short range correlations. The included correlations bring to a single step reaction mechanism and suggest an intriguing connection of this formalism with $0\nu\beta\beta$. MDCE cross section can be factorized into a unit cross section, describing the reaction features and nuclear matrix elements for the target and projectile transitions. This way to represent the theory is particularly promising as it mimics the factorization of the $0\nu\beta\beta$ decay rate, with special emphasis on the NME for the two processes, which appear to be intimately linked. The results of first numerical calculations compared with experimental DCE data are very encouraging, signaling that both the absolute value and the diffraction pattern of the angular distributions are reasonably well described [40]. Final refinements are in progress, the most important one being the need to add coherently the MDCE and DSCE reaction amplitudes in order to account for their interference.

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