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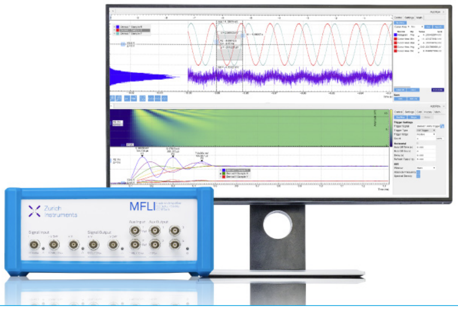

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Abstract: The NUMEN project aims at accessing experimentally driven information on Nuclear Matrix Elements (NME) involved in the half-life of the neutrinoless double beta decay ($0\nu\beta\beta$), by high-accuracy measurements of Heavy Ion (HI) induced Double Charge Exchange (DCE) reaction cross sections. In particular, the (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) reactions are used as tools for $\beta^+\beta^+$ and $\beta^-\beta^-$ decays, respectively. In the experiments, performed at INFN - Laboratory Nazionali del Sud (LNS) in Catania, the beams are accelerated by the Superconducting Cyclotron (CS) and the reaction ejectiles are detected the MAGNEX magnetic spectrometer. The measured cross sections are challengingly low (a few nb), being the total reaction cross section much larger (a few b), thus a high sensitivity and a large rejection capability are demanded to the experimental set-up. This limits the present exploration to few selected isotopes of interest in the context of typically low-yield experimental runs. A major upgrade of the LNS facility is foreseen in order to increase the experimental yield of at least two orders of magnitude, still keeping the high sensitivity of the present set-up, making it feasible a systematic study of all the cases of interest. Frontiers technologies are going to be developed, to this purpose, for the accelerator and the detection systems. In parallel, advanced theoretical models are being developed in order to extract the nuclear structure information from the measured cross sections.

INTRODUCTION

The neutrinoless double beta decay ($0\nu\beta\beta$) is nowadays the most promising resource to establish the Majorana nature of neutrinos and potentially to shed light on the absolute neutrino mass and hierarchy. A critical aspect is that the associated Nuclear Matrix Elements (NME) must be known with good accuracy, despite the intrinsic many-body nature of the involved states of the parent and daughter nuclei makes this task particularly demanding. An updated comparison of the results of NME calculations, obtained within various nuclear structure frameworks [1-4], indicates that significant differences are indeed found, which makes the present situation not satisfactory. In addition, some assumption common to different competing calculations, like the unavoidable truncation of the nuclear many body wave-function, could cause overall systematic uncertainties.

NUMEN [5-7] proposes to use HI-DCE reactions as tools to access quantitative information, relevant for $0\nu\beta\beta$ decay NME. These reactions are characterized by the transfer of two charge units, leaving the mass number unchanged, and can proceed by a sequential nucleon-transfer mechanism or by exchange of two isovector mesons, in an uncorrelated or correlated fashion. Despite $0\nu\beta\beta$ decays and HI-DCE reactions are mediated by different interactions, they present a number of similarities. Among those, the key aspects are that initial and final nuclear states are the same and the transition operators in both cases present a superposition of short-range isospin, spin-isospin and rank-two tensor components with a relevant available momentum (100 MeV/c or so).

STATUS OF THE PROJECT

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 promotes and is strictly connected with a renewal of the INFN-LNS research infrastructure and with a specific R&D activity on detectors, materials and instrumentation.

In the last years the project has been developing (NUMEN Phase2) following a threefold scheme: measuring DCE cross sections for a few cases of interest; making a deep R&D investigation for the new detection technologies to be used for the future high luminosity beams; developing a fully microscopic and quantum theory for DCE reactions, specifically conceived to extract nuclear structure information from measured cross sections. Below some of the main achievements of this activity is outlined.

THE EXPERIMENTS

The experimental campaigns have been conducted so far at INFN-LNS, using the K800 Superconducting Cyclotron to accelerate beams and the MAGNEX large acceptance magnetic spectrometer for the detection of the ejectiles.

MAGNEX is a large acceptance magnetic device made up of a large aperture vertically focusing quadrupole and a horizontally bending dipole magnet. It allows the identification of heavy ions with quite high mass ($\Delta A/A \sim 1/160$), angle ($\Delta\theta \sim 0.2°$) and energy resolutions ($\Delta E/E \sim 1/1000$), within a large solid angle ($\Omega \sim 50$ msr) and momentum range ($-14\% < \Delta p/p < +10\%$). High-resolution measurements for quasi-elastic processes, characterized by differential cross-sections falling down to tens of nb/sr, were already performed by this setup [8-13]. A crucial feature is the implementation of a technique of trajectory reconstruction, based on differential algebraic techniques, which allows solving the equation of motion of each detected particle to 10th order [14].

The experimental activity proposed and presently in progress consists of two main classes of experiments, corresponding to the exploration of the two directions of isospin lowering $\tau - \tau -$ and rising $\tau + \tau +$, characteristic of $\beta^-\beta^-$ and $\beta^+\beta^+$ decays respectively [15-17].

Experiments with ^{18}O Beam ($\beta^+\beta^+$ Direction)

For the experiments of this class, the reaction channels of our interest are: elastic and inelastic scattering (^{18}O,^{18}O); DCE reaction (^{18}O,^{18}Ne); charge-exchange reaction (^{18}O,^{18}F); two-proton pickup reaction (^{18}O,^{20}Ne); one-proton pickup reaction (^{18}O,^{19}F); two-neutron stripping reaction (^{18}O,^{16}O); one-neutron stripping reaction (^{18}O,^{17}O).

One of the main challenges of such experiments is the measurement at very forward angles, including zero-degree. This is performed by placing the spectrometer with its optical axis at +3° with respect to the beam axis. Thanks to its large angular acceptance, a range $-2° < \theta_{lab} < 9°$ is thus covered.

^{116}Sn, ^{76}Se and ^{48}Ti are the targets already explored via (^{18}O,^{18}Ne) reaction at 15 and 22 AMeV in order to study the ^{116}Sn → ^{116}Cd, ^{76}Se → ^{76}Ge and ^{48}Ti → ^{48}Ca transitions, respectively, and the competing channels as mentioned above. The reduction and analysis of the collected data is presently in progress.

Experiments with ^{20}Ne Beam ($\beta^-\beta^-$ Direction)

In the class of experiments with ^{20}Ne^{10+} beams, the reaction channels we are interested are the following: Elastic and inelastic scattering (^{20}Ne,^{20}Ne); DCE reaction (^{20}Ne,^{20}O); Charge Exchange reaction (^{20}Ne,^{20}F); Two-proton stripping reaction (^{20}Ne,^{18}O); One-proton stripping reaction (^{20}Ne,^{19}F); Two-neutron pickup reaction (^{20}Ne,^{22}Ne); One-neutron pickup reaction (^{20}Ne,^{21}Ne).

The spectrometer optical axis is typically placed at −3°, thus the covered angular range is $-8° < \theta_{lab} < +3°$.

A peculiarity of these experiments is that the beam components ^{20}Ne^{9+} and 20Ne8+, produced by the interaction of the beam with the electrons of the target material, have a magnetic rigidity similar to the ions of interest. Therefore, they enter in the FPD acceptance, causing a limitation in the rate tolerable by the detector. In order to mitigate this problem two aluminium shields are mounted upstream the sensitive region of the focal plane detector. In addition, an appropriate second foil (post-stripper) is mounted downstream of the isotopic target. Recently a specific study of different materials to be used as post-stripper has been performed [18].

The systems already experimentally explored using the (^{20}Ne,^{20}O) reaction at 15 AMeV are the ^{116}Cd target (to study the ^{116}Cd → ^{116}Sn transition), the ^{130}Te (for the ^{130}Te → ^{130}Xe) and the ^{76}Ge (for the ^{76}Ge → ^{76}Se). The data reduction and analysis is in progress.

FEATURES OF R&D

The results of NUMEN Phase 1 indicate that suitable information from DCE reactions can be extracted [8]. However, for a systematic exploration of all the cases of interest for 0vbb a much larger dataset of DCE data is necessary, including statistically significant data at different bombarding energies and with several isotopic targets.

These considerations suggest that the DCE experiments should be performed with much higher beam current. In particular, for a systematic study of the many “hot” cases of $\beta\beta$ decays, an upgraded set-up, able to work with a two or three orders of magnitude higher current than the present, is necessary. 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) must be sensibly revised. This goal can be achieved by a substantial change in the technologies implemented in the beam extraction, in the detection of the ejectiles and in the target cooling. For the accelerator the change of the beam extraction technology from electrostatic deflector to a stripper foil is an adequate choice [19]. For the spectrometer the main foreseen upgrades are:

1. The construction of a FPD tracker based on micro patterned gas detector [20];
2. The construction of a wall of telescopes of SiC-CsI detectors for ion identification [21-22];
3. The introduction of an array of scintillators for measuring the coincident γ-rays;
4. The development of suitable front-end and read-out electronics, for a fast read-out of the detector signals, a high signal to noise ratio and adequate hardness to radiation [23];

5. The implementation of a suitable architecture for data acquisition, storage and data handling, including accurate detector response simulations;
6. The enhancement of the maximum accepted magnetic rigidity, with minimal distortion of the measured magnetic field for the optical elements [24-25];
7. The installation of a beam dump to stop the high power beams.

In addition, we are developing the technology for suitable nuclear targets to be used in the experiments. Here the challenge is to produce and cool isotopically enriched thin films able to resist to the high power dissipated by the interaction of the intense beams with the target [26].

DEVELOPMENT OF DCE THEORY

NUMEN is fostering the development of a specific theory program to allow an accurate extraction of nuclear structure information from the measured cross sections.

In ref. [27-28] the heavy ion induced Single Charge Exchange (SCE) have been described in the view of the connection to single beta decay NME. It was shown that the surface localization of the SCE, due the strong absorption of the target-projectile nucleus-nucleus potential, allows for a strong simplification of the reaction description, making the isovector meson exchange mechanism relevant at forward detection angles.

The development of a second order perturbation theory for DCE is being accomplished 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 $0\nu\beta\beta$ decay and DCE reactions [28-30].

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