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The nuclear matrix elements of 0νββ decay and the NUMEN project at INFN-LNS

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Abstract

An innovative technique to access the nuclear matrix elements entering the expression of the life time of the double beta decay by relevant cross section measurements of double charge exchange reactions is proposed. A key aspect of the project is the use of the MAGNEX large acceptance magnetic spectrometer, for the detection of the ejectiles, and of the LNS K800 Superconducting Cyclotron (CS), for the acceleration of the required high resolution and low emittance heavy-ion beams, already in operation at INFN Laboratory Nazionali del Sud in Catania (Italy). However, a major upgrade is foreseen for the INFN-LNS research infrastructure to cope with beam currents as high as several pμA required by the project.

1 Introduction

Neutrinoless double beta decay, 0νββ, is at the present time strongly pursued both experimentally and theoretically [1]. Its observation will determine whether the neutrino is a Dirac or Majorana particle and will provide a measurement of the average neutrino mass, which is nowadays

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one of the fundamental problems in physics. An innovative technique to access the Nuclear Matrix Elements (NME) entering the expression of the life time of the $0\nu\beta\beta$ by relevant cross sections of double charge exchange (DCE) reactions is proposed. The basic point is the coincidence of the initial and final state wave-functions in the two classes of processes and the similarity of the transition operators, which in both cases present a superposition of Fermi, Gamow-Teller and rank-two tensor components with a relevant momentum available.

First pioneering experimental results, obtained at the INFN-LNS laboratory in Catania, for the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction at 270 MeV, in a wide range of transferred momenta, give encouraging indication on the capability to access quantitative information towards the determination of the NME for $0\nu\beta\beta$ decay [2]. On the basis of the above mentioned ground-breaking achievement, we propose an ambitious project, NUMEN, with the aim to go deep insight in the Heavy Ion DCE studies on nuclei of interest for $0\nu\beta\beta$ decay [3].

There are a number of important similarities among DCE and $0\nu\beta\beta$ decay processes, despite they are mediated by different interactions. The description of NMEs extracted from DCE and $0\nu\beta\beta$ 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 $\beta\beta$-decay half-lives is not trivial and needs to be explored.

1.1 The Project

The availability of the MAGNEX spectrometer [4] for high resolution measurements of very suppressed reaction channels was essential for the first pilot experiment. Moreover, the measurement of DCE high resolution energy spectra and accurate cross sections at very forward angles are key points to identify the transitions of interest [5]. The concurrent measurement of the other relevant reaction channels allows to isolate the direct DCE mechanism from the competing transfer processes. These are at least of 4th-order and can be effectively minimized by the choice of the proper projectile-target system and incident energy [6].

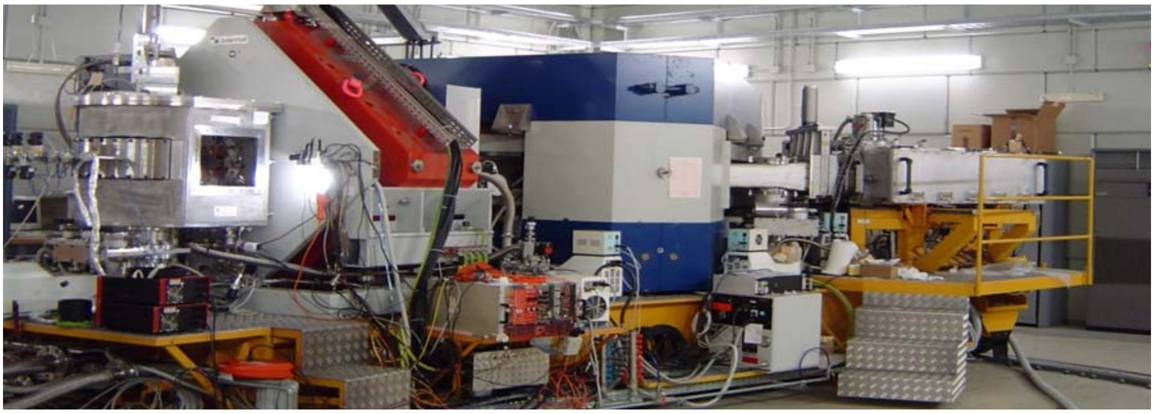

Fig.1: A view of MAGNEX spectrometer at Laboratori Nazionali del Sud in Catania.

Fig.2: A view of K800 Superconducting Cyclotron at Laboratori Nazionali del Sud in Catania.

The present limit of low beam current we have experienced both for the CS accelerator and for the MAGNEX focal plane detector must be sensibly overcome. For a systematic study of the many "hot" cases of ββ decays an upgraded set-up, able to work with two orders of magnitude more current than the present, is thus necessary. This goal can be achieved by a substantial change in the technologies used in the beam extraction and in the detection of the ejectiles. For the accelerator the use of a stripper induced extraction is an adequate choice. However, with the present set-up it is difficult to suitably extend this research to the "hot" cases, where ββ decay studies are and will be concentrated. For the spectrometer the main foreseen upgrades are:

1. The substitution of the present Focal Plane Detector (FPD) [7-8] technology with tracker based on a micro-pattern electron amplifier;
2. The substitution of the wall of silicon pad stopping detectors with a wall of telescopes based on Silicon Carbide detectors;
3. The enhancement of the maximum magnetic rigidity;
4. The introduction of an array of detectors for measuring the coincident γ-rays.

In this framework we propose four phases in the NUMEN project, looking forward to do, in the same time, both the experimental and the up-grade activity, as indicated in the following Phases of the project.

Phase1: the experiment feasibility

The pilot experiment: ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar reaction at 270 MeV, with the first experimental data on heavy-ion DCE reactions in a wide range of transferred momenta, was already done. The results demonstrate the technique feasibility.

Phase2: toward "hot" cases optimizing experimental conditions and getting first results

The necessary work for the upgrading of both the accelerator and MAGNEX will be carried out still preserving the access to the present facility. Due to the relevant technological challenges connected, in which test, with and without beam will be crucial, the Phase2 is foreseen to have a duration of a 3-4 years. In the meanwhile, experiments with integrated charge of tens of mC (about one order of magnitude more than that collected in the pilot experiment) will be performed. These will require several weeks (4-8 depending on the case) data taking for each reaction, since thin targets (a few 10^{18} atoms/cm^2) are mandatory in order to achieve enough energy and angular resolution in the energy spectra and angular distributions. The attention will be focused on a few favorable cases, like for example ^{116}Sn (^{18}O,^{18}Ne)^{116}Cd reaction at 15 and 30 MeV/u and the ^{116}Cd (^{20}Ne,^{20}O)^{116}Sn reaction at 15 and 25 MeV/u, with the goal to achieve conclusive results for them.

Phase3: the facility upgrade

Once all the building block for the upgrade of the accelerator and spectrometer facility will be ready at the LNS a Phase3, connected to the disassembling of the old set-up and re-assembling of the new will start. An estimate of about 18-24 months is considered.

Phase4: the experimental campaign

The Phase4 will consist of a series of experimental campaigns at high beam intensities (some pμA) and long experimental runs in order to reach in each experiment integrated charge of hundreds of mC up to C, for the experiments in coincidences, spanning all the variety of candidate isotopes for $0\nu\beta\beta$ decay, like:

^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{110}Pd, ^{124}Sn, ^{128}Te, ^{130}Te, ^{136}Xe, ^{148}Nd, ^{150}Nd, ^{154}Sm, ^{160}Gd, ^{198}Pt.

1.1.1 The NUMEN goals

Studying if the DCE reaction mechanism can be reliably factorized in a reaction part and a nuclear structure part, this latter factorized in a projectile and target matrix element is a main purpose of NUMEN. The development of a consistent microscopic description of the heavy-ion double charge exchange reaction and the nuclear structure part is essential to 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.

Moreover, the project has two other goals, ground-breaking and achievable in a shorter period. The measured DCE absolute cross sections provide themselves 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 allows to test the goodness of the assumptions done for the unavoidable truncation of the many-body wave functions. The reaction part need 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 neutrino-less double 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 “hot cases” of the $0\nu\beta\beta$ decay. In 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 sizeable 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 in the future developments of the field, especially in a scenario were fundamental choices for the best isotope candidates for $0\nu\beta\beta$ decay need to be done.

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