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NUMEN Project @ LNS : Heavy Ions Double Charge Exchange as a tool towards the $0\nu\beta\beta$ Nuclear Matrix Element

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Abstract. The NUMEN Project, proposed at INFN Laboratori Nazionali del Sud (LNS) in Catania, has the aim to access the nuclear matrix elements, entering the expression of the life time of double beta decay, by relevant cross sections of double charge exchange reactions. The basic point, on which it is based this innovative technique, is the coincidence of the initial and final state wave-functions in the two classes of processes and the similarity of the transition operators. A key aspect of the Project is the use of MAGNEX large acceptance magnetic spectrometer, for the detection of the ejectiles, and of the INFN LNS K800 Superconducting Cyclotron (CS), for the acceleration of the required high resolution and low emittance heavy-ion beams.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is potentially the best resource to probe the Majorana or Dirac nature of neutrino and to extract its effective mass. Presently, this physics case is one of the most important research “beyond the Standard Model” and might guide the way towards a Grand Unified Theory of fundamental interactions.

Since the $\beta\beta$ decay process involves transitions in atomic nuclei, nuclear structure issues must be accounted for. The $0\nu\beta\beta$ decay rate $[T_{1/2}]^{-1}$ can be factorized as a phase-space factor $G_{0\nu}$, the nuclear matrix element (NME) $M_{0\nu}$ and a term $f(m_i, U_{ei})$ containing the masses m_i and the mixing coefficients U_{ei} of the neutrino species:

$$[T_{1/2}]^{-1} = G_{0\nu} |M_{0\nu}|^2 |f(m_i, U_{ei})|^2$$



The NME is defined as the transition amplitude from the initial to the final nuclear state of the $\beta\beta$ process through the $0\nu\beta\beta$ decay operator. Thus, if the NMEs are established with sufficient precision, the neutrino masses and the mixing coefficients can be extracted from $0\nu\beta\beta$ decay rate measurements.

The evaluation of the NMEs is presently limited to state of the art model calculations based on different methods (QRPA, shell-model, IBM etc.) [1], [2], [3], [4]. However the ambiguities in the models are still too large and the constraints too loose to reach accurate values of the NMEs. Discrepancy factors higher than two are presently reported in literature [5].

In this picture, we suggest an innovative technique in the NUMEN (Nuclear Matrix Elements of Neutrinoless Double Beta Decay) Project [6]: the idea is to use for the first time Heavy-Ions Double Charge Exchange (HI-DCE) cross section measurements towards the $0\nu\beta\beta$ NME determination.

2. DCE reactions and neutrinoless double beta decays

There are a number of important similarities among DCE and $0\nu\beta\beta$ decay processes, despite they are mediated by different interactions. 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 component. Moreover a large linear momentum (~ 100 MeV/c) is available in the virtual intermediate channel in both processes; the two processes are non-local and are characterized by two vertices localized in a pair of valence nucleons; both processes take place in the same nuclear medium; a relevant off-shell propagation through virtual intermediate channels is present in the two cases.

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.

The use of modern high resolution and large acceptance spectrometers, like MAGNEX, together with high resolution and low emittance heavy-ion beams, like that produced at LNS K800 Superconducting Cyclotron (CS), are crucial for the experimental challenges, looking forward to extract quantitative information from DCE reactions. 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 [7]. 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 [8].

First experimental results [9], obtained at the INFN-LNS laboratory in Catania, for the $^{40}\text{Ca}(^{18}\text{O}, ^{18}\text{Ne})^{40}\text{Ar}$ 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 Nuclear Matrix Elements for $0\nu\beta\beta$ decay.

On the basis of the above mentined ground-breaking achievement, we propose an ambitious project, NUMEN, with the aim to go deep insight in the HI-DCE studies on nuclei of interest in $0\nu\beta\beta$ decay, looking forward at the $0\nu\beta\beta$ NME dermination.

3. Toward the “hot” cases

The availability of the MAGNEX spectrometer [10] for high resolution measurements of very suppressed reaction channels was essential for the first pilot experiment [9]. However with the present set-up it is difficult to suitably extend this research to the “hot” cases, where $\beta\beta$ decay studies are and will be concentrated. The present limit is the low beam current we have experienced both for the CS accelerator and for the MAGNEX focal plane, that must be sensibly overcome. For a systematic study of the many “hot” cases of $\beta\beta$ decays an upgraded set-up, able to work with two orders of magnitude more current than the present, is 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 spectrometer the main foreseen upgrades are: the substitution of the present Focal Plane Detector (FPD) [11] gas tracker with a GEM tracker system; the substitution of the wall of silicon pad stopping detectors with a wall of telescopes based on SiC-CsI detectors; the enhancement of the maximum magnetic rigidity; 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.

3.1 *Phase1: the experiment feasibility*

The pilot experiment $^{40}\text{Ca}(^{18}\text{O}, ^{18}\text{Ne})^{40}\text{Ar}$ reaction at 270 MeV, with the first experimental data on heavy-ion double charge-exchange reactions in a wide range of transferred momenta, was already done. The results demonstrate the technique feasibility [9].

3.2 *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 data taking for each reaction, since thin targets (a few 10^{18} atoms/cm²) 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, with the goal to achieve conclusive results for them.

3.3 *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 one, will start.

3.4 *Phase4: the experimental campaign*

The Phase4 will consist of a series of experimental campaigns at high beam intensities (some μA) 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 .

4. Perspectives

To perform the experimental campaign that we propose it is necessary the LNS CS upgrade to give high beam intensity and the upgrade of the detection system. Actually, we require a new focal plane detector, suitable to resist to high rates, and a modular gamma detector system that, together, allows us to complete the last phase of measurements, spanning among all the nuclei of interest for our studies. Once selected the optimal experimental condition for the different cases, as planned in the NUMEN project Phase2, with the upgrades mentioned above, the Phase4 will be devoted to collect data. These data will be addressed to give, with an accurate analysis, a rigorous determination of the absolute cross sections values and their uncertainties for all the system of interest. This is the way the NUMEN Project aims to access NME, entering the expression of the life time of double beta decay, that is its most ambitious goal.

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