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The NUMEN Project @ LNS: Status and perspectives

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Summary. — 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 the cross sections of Heavy Ion (HI) induced Double Charge Exchange (DCE) reactions. Particular attention is given to the (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) reactions as tools for $\beta^+\beta^+$ and $\beta^-\beta^-$ decays, respectively. First evidence about the possibility to get quantitative information about NME from experiments is found for both kind of reactions. 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 products are detected by the MAGNEX magnetic spectrometer. The measured cross sections are challengingly low, limiting 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, thus making 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 will be developed in order to extract the nuclear structure information from the measured cross sections.

1. – Introduction

The $0\nu\beta\beta$ decay of atomic nuclei is a still unobserved but possible natural phenomenon which is attracting a growing interest in the physics community. The main reason for such interest is that besides establishing the Majorana nature of neutrinos, $0\nu\beta\beta$ decay has the potential 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 difficult. 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 [5,6] 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 meson-exchange. 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 (τ), spin-isospin ($\sigma\tau$) and rank-two tensor components with a sizeable available momentum (100 MeV/c or so).

The main experimental tools for this project are the high resolution Superconducting Cyclotron beams and the MAGNEX spectrometer. The latter is a large acceptance magnetic system characterized by high resolution in energy, mass and angle [7] and an accurate control of the detection efficiency. The implementation of trajectory reconstruction technique is the key feature of MAGNEX, which guarantees the above mentioned performance and its relevance in the research for heavy-ion physics [8-10], also taking advantage of its coupling to the EDEN neutron detector array [11,12].

2. – The phases of the NUMEN Project

The NUMEN project 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, this 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. NUMEN is divided into the following four phases, each one delimited by a starting point and defined by the fulfilment of an intermediate goal, which is necessary for the development of the successive phase.

Phase 1: *"The pilot experiment"* - In 2013, the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar DCE reaction was measured at the INFN-LNS laboratory together with the competing processes: ^{40}Ca(^{18}O,^{18}F)^{40}K Single Charge Exchange (SCE), ^{40}Ca(^{18}O,^{20}Ne)^{38}Ar two-proton (2p) transfer and ^{40}Ca(^{18}O,^{16}O)^{42}Ca two-neutron (2n) transfer [13]. This work showed for the first time high resolution and statistically significant experimental data on DCE reactions in a wide range of transferred momenta. The measured cross-section angular distribution is characterized by a clear oscillating pattern, remarkably described by an L = 0 Bessel function, indicating that a simple mechanism is dominant in the DCE reaction. This is confirmed by the observed suppression of the multi-nucleon transfer routes.

DCE matrix elements were extracted under the hypothesis of a two-step charge exchange process. Despite the approximations used in our model, which determine an uncertainty of ±50%, the obtained results are compatible with the values known from literature, indicating that the main physics content has been kept.

Phase 2: *From the pilot experiment toward the "hot" cases* - The results of Phase 1 indicate that suitable information from DCE reactions can be extracted. The availability of the MAGNEX spectrometer for high resolution measurements of much more suppressed reaction channels was essential for such a pioneering measurement. However, with the present set-up, it is difficult to suitably extend this research to the "hot" cases, where $\beta\beta$ decay studies are concentrated. We consider that:

1. In the studied reaction, the Q-value was particularly favourable (Q = -2.9 MeV), while in the DCE reactions involving candidate isotopes of interest for $0\nu\beta\beta$ the Q-values are more negative. This is expected to produce a sensible reduction of the cross-section in these cases, especially at very forward angles.

2. The isotopes of interest are heavier than ^{40}Ca, consequently the nucleus-nucleus potential in the initial and final state (ISI and FSI) are more absorptive with consequent further reduction of the cross section for direct reactions as DCE.

3. The DCE cross section is expected to decrease at higher bombarding energies (at least in the energy range explored by NUMEN, i.e. 10 to 70 MeV/u) since both τ and $\sigma\tau$ components of the nucleon-nucleon effective potential show this trend. This aspect is particularly relevant considering that direct DCE cross section is sensitive to the 4th power of the potential strength.

4. The (^{18}O,^{18}Ne) reaction, investigated in the pilot experiment, could be particularly advantageous, due to the large value of both the B[GT; $^{18}\mathrm{O_{gs}}(0^+) \rightarrow$ $^{18}\mathrm{F_{gs}}(1^+)$] and B[GT; $^{18}\mathrm{F_{gs}}(1^+) \rightarrow$ $^{18}\mathrm{Ne_{gs}}(0^+)$] Gamow-Teller strenghts and to their concentration in the $^{18}\mathrm{F}(1^+)$ ground state. However, this reaction is of $\beta^+\beta^+$ kind, while most of the research on $0\nu\beta\beta$ decay is on the $\beta^-\beta^-$ side. None of the reactions of $\beta^-\beta^-$ kind looks like as favorable as the (^{18}O,^{18}Ne). For example, the (^{18}Ne,^{18}O) requires a radioactive beam, which cannot be available with enough intensity. NUMEN proposes the (^{20}Ne,^{20}O) reaction, which has smaller B(GT), so a reduction of the yield could be foreseen in these cases.

5. In some cases, e.g. ^{136}Xe or ^{130}Xe, gas or implanted target will be necessary, which are normally much thinner than solid state films obtained by evaporation or rolling technique, with a consequent reduction of the collected yield.

6. The achieved energy resolution (typically about half MeV) is not always enough to separate the ground from the excited states in the final nucleus. In these cases the coincident detection of γ-rays from the de-excitation of the populated states is necessary, but at the price of reducing the yield.

All of 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 ($\sim$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 [14]. For the spectrometer the main foreseen upgrades are:

1. The substitution of the present focal plane detector (FPD) gas tracker, based on multiplication wire technology with a tracker system based on micro patterned gas detector [15,16];

2. The substitution of the wall of silicon pad stopping detectors with telescopes of SiC-CsI detectors [17,18] or similar [19];

3. The introduction of an array of scintillators for measuring the coincident γ-rays [20];

4. The development of suitable front-end and read-out electronics, capable to guarantee a fast read-out of the detector signals, still preserving a high signal to noise ratio and guaranteeing enough hardness to radiation [21,22];

5. Develop a suitable architecture for data acquisition, storage and data handling, including accurate detector response simulations;

6. The enhancement of the maximum accepted magnetic rigidity, preserving the geometry and field uniformity of the magnetic field [23-26] in order to keep the high-precision of the present trajectory reconstruction;

7. The installation of a beam dump to stop the high power beams, keeping the generated radioactivity under control.

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 material [27-29].

During the NUMEN Phase 2, the R&D activity necessary for the above mentioned upgrades is going on still preserving the access to the present facility. In the meanwhile, experiments with integrated charge of tens of mC (about one order of magnitude higher than that collected in the pilot experiment) are being performed. These require several weeks of data taking for each reaction, since thin targets (a few 10^{18} atoms/cm^2) are mandatory in order to get enough energy and angular resolution in the measured energy spectra and angular distributions. The attention is presently focused on a few favorable candidate cases for $\beta\beta$ decay, with the goal to achieve conclusive results for them. In addition, during Phase 2 a deeper understanding of the main features which limit the experimental sensitivity, resolution and systematic errors is being pursued.

In this framework, we study the (^{18}O,^{18}Ne) reaction as a probe for the $\beta^+\beta^+$ transitions and the (^{20}Ne,^{20}O), or alternatively (^{12}C,^{12}Be), for the $\beta^-\beta^-$, with the aim to explore the DCE mechanism in both directions. Since NMEs are time invariant quantities, they are common to a DCE and to its inverse, so the contextual measurements of $\beta^+\beta^+$ and $\beta^-\beta^-$ reactions represent a useful test bench of the procedure to extract NME from measured DCE cross section.

The choice of the target isotopes is a result of a compromise between the interest of the scientific community to specific isotopes and technical issues. In particular, the possibility to separate g.s. to g.s. transition in the DCE measured energy spectra and the availability of thin uniform target of isotopically enriched material was considered. We started by selecting two systems, the ^{116}Cd-^{116}Sn and ^{76}Ge-^{76}Se pairs. For these nuclei the ground states are resolved from excited states by MAGNEX (being respectively 562 keV for ^{76}Ge, 559 keV for the ^{76}Se, 1.29 MeV for ^{116}Sn and 513 keV for ^{116}Cd) for both (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) reactions [30]. In addition, the production technologies of the thin targets are already available at INFN-LNS. We are also exploring the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe reaction. For each system, the complete net of reactions involving the multi-step transfer processes, characterized by the same initial and final nuclei are studied under the same experimental conditions.

During the Phase 2 the data reduction strategy is being optimized and the relevant theoretical aspects studied [31,32]. In particular, NUMEN is fostering the development of a specific theory program to allow an accurate extraction of nuclear structure information from the measured cross sections. 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.

The experimental activity of NUMEN Phase 2 and the analysis of the collected results is the main aspect of the NURE project [33] recently awarded by the European Reseach Council. The synergy between the two projects is an added value which significantly enhance the discovery potential already in NUMEN Phase 2.

Phase 3: *The facility upgrade* - Once all the building blocks for the upgrade of the whole facility will be ready at the INFN-LNS, the NUMEN Phase 3, consisting in the disassembling of the old set-up and reassembling a new will start. An estimate of about 18-24 months is evaluated. During this period, the data analysis of the NUMEN Phase 2 experiments will continue. In addition, tests of the new detectors and selected experiments will be performed with Tandem beams at INFN-LNS and in other laboratories in order to provide possible pieces of still missing information.

Phase 4: *The experimental campaign with upgraded facility* - The NUMEN Phase 4 will consist of a series of experimental campaigns at high beam intensities (some particle-μA) and integrated charge of hundreds of mC up to C, for the experiments in which γ-coincidence measurements are required, spanning all the variety of $0\nu\beta\beta$ decay candidate isotopes, like: ^{48}Ca, ^{76}Ge, ^{76}Se, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{106}Cd, ^{110}Pd, ^{116}Cd, ^{110}Sn, ^{124}Sn, ^{128}Te, ^{130}Te, ^{136}Xe, ^{130}Xe, ^{148}Nd, ^{150}Nd, ^{154}Sm, ^{160}Gd, ^{198}Pt. Based on the know-how gained during the experimental activity of Phase 2, the Phase 4 will be devoted to determine the absolute DCE cross sections and their uncertainties. Hopefully, the use of improved theoretical analyses will give access to the challenging NMEs $0\nu\beta\beta$ decay that is the ambitious goal of NUMEN.

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