The role of nuclear reactions in the problem of *0vββ* 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 sections of double charge exchange 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 implicit momentum transfer. First pioneering experimental results obtained at the INFN-LNS laboratory for the $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ reaction at 270 MeV, give encouraging indication on the capability of the proposed technique to access relevant quantitative information. A key aspect of the project is the use of the K800 Superconducting Cyclotron (CS) for the acceleration of the required high resolution and low emittance heavy-ion beams and of the MAGNEX large acceptance magnetic spectrometer for the detection of the ejectiles. The use of the high-order trajectory reconstruction technique, implemented in MAGNEX, allows to reach the high mass, angular and energy resolution required even at very low cross section. The LNS set-up is today an ideal one for this research even in a worldwide perspective. However a main limitation on the beam current delivered by the accelerator and the maximum rate accepted by the MAGNEX focal plane detector must be sensibly overcome in order to systematically provide accurate numbers to the neutrino physics community in all the studied cases. The upgrade of the LNS facilities in this view is part of this project.

1. A basic question in modern physics

Neutrinoless double beta decay (*0vββ*) is potentially the best resource to probe the Majorana or Dirac nature of neutrino and to extract its effective mass. Moreover, if *0vββ* is observed, it would signal that the total lepton number is not conserved. Presently, this physics case is one of the most important researches "beyond the Standard Model" and might guide the way towards a Grand Unified Theory of fundamental interactions. The *0vββ* decay rate $[T_{1/2}]^{-1}$ can be factorized as a phase-space factor G_{0v}, the nuclear matrix element (NME) M_{0v} and a term $f(m_i,U_{ei})$ containing the masses m_i and the mixing coefficients U_{ei} of the neutrino species:

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

where the NME is the transition amplitude from the initial $|\varphi_i\rangle$ to the final $|\varphi_f\rangle$ nuclear state of the $\beta\beta$ process through the $0\nu\beta\beta$ decay operator:

$$|M_{0\nu}|^2 = \left|\langle\varphi_f|O^{0\nu\beta\beta}|\varphi_i\rangle\right|^2 \qquad (2)$$

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]. High precision experimental information from single charge-exchange, transfer reactions and electron capture are used to give constraints to the calculations [5], [6], [7], [8] [9]. However the ambiguities in the models are still too large and the constraints too loose to reach accurate values of the NMEs. Discrepancies higher than two are presently reported in literature [10]. In addition some assumptions, common to the different competing calculations, could cause overall systematic uncertainties [11].

The experimental study of nuclear transitions where the nuclear charge is changed by two units leaving the mass number unvaried, in analogy to the $\beta\beta$-decay, could give important information. The availability for the first time of valuable data on Double Charge Exchange (DCE) reactions raises the question whether they can be used toward the experimental access to $0\nu\beta\beta$ NMEs. Despite the DCE and $0\nu\beta\beta$ decay processes are mediated by different interactions, there are a number of important similarities among them:

1. Parent/daughter states of the $0\nu\beta\beta$ decay are the same as those of the target/residual nuclei in the DCE;

2. Short-range Fermi, Gamow-Teller and rank-2 tensor components are present in both the transition operators, with relative weight depending on incident energy in DCE;

3. A large linear momentum (~100 MeV/c) is available in the virtual intermediate channel in both processes. This is a crucial similarity since the $0\nu\beta\beta$ NMEs strongly depend on the momentum transfer and other processes cannot probe this feature;

4. The two processes are non-local and are characterized by two vertices localized in a pair of valence nucleons;

5. Both processes take place in the same nuclear medium, thus quenching phenomena are expected to be similar. In particular in both β-decay [4] and charge exchange reactions [12] the limited model space used in the calculations and the contribution of non-nucleonic degrees of freedom and other correlations require a renormalization of the coupling constants in the spin-isospin channel.

6. 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.

2. The pioneering experiment

The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ DCE reaction was measured at the INFN-LNS in Catania (Italy) together with the competing processes: $^{40}Ca(^{18}O,^{18}F)^{40}K$ single charge-exchange, $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ two-proton and

^{40}Ca(^{18}O,^{16}O)^{42}Ca two-neutron transfer. The experiments were performed using an ^{18}O beam accelerated by the LNS Superconducting Cyclotron (CS) at 270 MeV incident energy and detecting the ejectiles by the MAGNEX large acceptance magnetic spectrometer [13] [14] [15].

This work shows for the first time experimental data on heavy-ion double charge-exchange reactions in a wide range of transferred momenta [16]. Strengths factors have been extracted under the hypothesis of a two-step charge-exchange process. Despite the approximations used in the comparison, they are reasonable within ±50%, signaling that the main physics content has been kept. A deeper investigation of DCE reactions is worthwhile in the future, studying other systems and different bombarding energies, in order to explore the systematic behavior. A rigorous treatment of the details, neglected in the present work, will be the next step toward the determination of the *0νββ* NMEs.

3.   The Phase2 of the NUMEN project: toward "hot" cases

The results mentioned above indicate that suitable information from heavy-ion induced DCE reactions can be extracted. In particular the determination of nuclear matrix elements for these processes seems to be at our reach and precious information toward *0νββ* matrix elements can be extracted. This is at the basis of a new project at the INFN, named NUMEN (NUclear Matrix Elements of Neutrinoless double beta decay), which aims at the determination of systematic information on the nuclear matrix elements of interest for *0νββ* by heavy-ion double charge exchange reactions.

The availability of the MAGNEX spectrometer for high resolution measurements of much 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 *ββ* decay studies are and will be concentrated. We consider that:

a)   About one order of magnitude more yield would have been necessary for the reaction studied, especially at backward angles where large amounts of linear momentum (1-2 fm^{-1}) are available;

b)   The (^{18}O,^{18}Ne) reaction is particularly advantageous, due to the large value of both the B[GT;^{18}Ogs(0$^+$)→ ^{18}Fgs(1$^+$)] and B[GT;^{18}Fgs(1$^+$)→ ^{18}Negs(0$^+$)] strengths and to the concentration of the GT strength in the ^{18}F(1$^+$) ground state. However this reaction is of *β$^+$β$^+$* kind, while most of the research on *0νββ* is on the opposite side;

c)   None of the reactions of *β$^-$β$^-$* kind looks like as favourable as the (^{18}O,^{18}Ne). For example the (^{18}Ne,^{18}O) requires a radioactive beam, which cannot be available with comparable intensity. The proposed (^{20}Ne,^{20}O) or the (^{12}C,^{12}Be) have smaller B(GT), so a sensible reduction of the yield is foreseen in these cases;

d)   In some cases gas target will be necessary, e.g. ^{136}Xe or ^{130}Xe, which are normally much thinner than solid state ones, with a consequent reduction of the collected yield;

e)   In some cases the energy resolution we can provide (about half MeV) is not enough to separate the ground state 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 the collected yield.

f)   A strong fragmentation of the double GT strength is known in the nuclei of interest compared to the ^{40}Ca.

Taking these considerations into account we realize that 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 $\beta\beta$ 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. More details about that are in the technical part of the project. For the spectrometer the main foreseen upgrades are:

1. The substitution of the present FPD gas tracker with a GEM tracker system;
2. The substitution of the wall of silicon pad stopping detectors with SiC detectors or similar;
3. The enhancement of the maximum magnetic rigidity;
4. The introduction of an array of detectors for measuring the coincident γ-rays.

The feasibility of DCE measurements at INFN-LNS with MAGNEX spectrometer, using the CS beams, was already demonstrated as explained before. To use this precious know-how for future application of this methodology to the relevant reaction of interest in the $0\nu\beta\beta$ search, we need to go through a Phase2. During the Phase2 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 the Phase2 is foreseen to have a duration of about 3-4 years. In the meanwhile, experiments with integrated charge of tens of mC (about one order of magnitude more than 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 favourable cases with the goal to achieve conclusive results for them.

2.1 Experimental activity at Phase2

The Phase2 is crucial to allow us to optimize the experimental conditions and open a new challenging research field, carrying out an experimental investigation of few candidate nuclei for the $\beta\beta$ decay. In this framework, we propose to study the (^{18}O,^{18}Ne) reaction as a probe for the $\beta^+\beta^+$ transitions and the (^{20}Ne,^{20}O), or alternatively the (^{12}C,^{12}Be), for the $\beta^-\beta^-$. We select two systems: the ^{76}Ge-^{76}Se pair for the first class and the ^{116}Cd-^{116}Sn pair for the second. For these nuclei the ground states are resolvable from excited states by MAGNEX (being respectively 562 keV ^{76}Ge, 559 keV for ^{76}Se, 1.29 MeV for ^{116}Sn and 513 keV for ^{116}Cd) and the production technologies of the thin targets are already available at LNS. We also plan to explore the ^{130}Te and ^{106}Cd systems [17], which are candidates for $0\nu\beta\beta$ already at our reach in terms of energy resolution and availability of thin targets. For each of them, the complete net of reactions involving the multi-step transfer processes, characterized by the same initial and final nuclei, as it is shown in Fig.1, will be studied under the same experimental conditions.
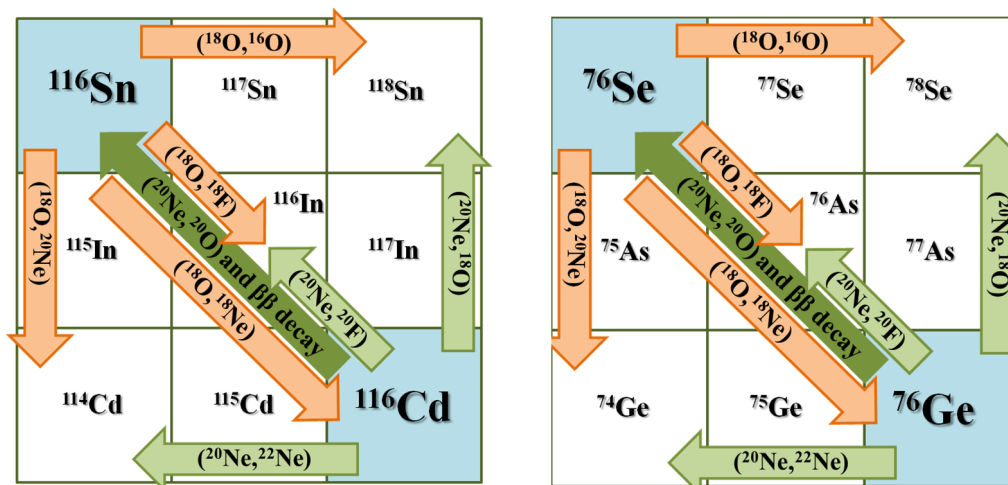
Figure 1: Scheme of the complete net of processes that will be studied in the case of the ^{116}Cd – ^{116}Sn and ^{76}Ge – ^{76}Se pairs of nuclei of interest for the $\beta\beta$ decay. Inside the arrows the reaction used to populate the final nuclei is indicated.

During the Phase2 the data reduction strategy will be optimized and the link with the theoretical physics will be strengthen, especially in the view of the construction of a "universal" framework, where $\beta\beta$-decay and DCE reactions are coherently analysed. The completion of the experimental activity of NUMEN Phase2 would represent by itself a ground-breaking result, looking forward the main goal of the proposal that has the ambition to indicate a new generation of experiments, with the challenging perspective, in the long term, to provide key information to the community to go deep insight the true nature of neutrino.

4.   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. During this period the group will be devoted to the data analyses, to the preparation of the next experiments and test of the new detectors with Tandem beams. In addition, if necessary, experiments on single charge exchange or transfer reactions will be performed in other laboratories in order to provide possible pieces of information still lacking, e.g. measurements of B(GT) or transfer amplitudes.

5.   Phase4: The experimental campaign

To perform the proposed experimental campaign, the upgrade of the CS accelerator is necessary 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. 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, 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.

Actually, once selected the optimal experimental condition for the different cases in the Phase2, with the aforementioned upgrades, the Phase4 will be devoted to collect data 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, to the challenging determination of the $0\nu\beta\beta$ decay nuclear matrix elements, that is the ambitious goal of the NUMEN project.

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