The NUMEN project: Heavy-Ion Double Charge Exchange reactions towards $0\nu\beta\beta$ NME determination

C. Agodi[1], F. Cappuzzello[1,2], D. Carbone[1], M. Cavallaro[1], L. Acosta[3], D. Bonanno[4], D. Bongiovanni[1], T. Borello[5], I. Boztosun[6], S. Calabrese[1,2], D. Calvo[7], E.R. Chávez Lomelí[3], N. Deshmukh[1], P.N. de Faria[8], P. Finocchiaro[1], M. Fisichella[7], A. Foti[2,4], G. Gallo[2,4], A. Hacisalihoglu[1,9], F. Iazzi[7,10], R. Introzzi[7], G. Lanzalone[1,11], R. Linares[8], F. Longhitano[4], D. Lo Presti[2,4], N. Medina[5], A. Muoio[1], J.R.B. Oliveira[5], A. Pakou[12], L. Pandola[1], F. Pinna[7,10], S. Reito[4], G. Russo[2,4], G. Santagati[1], O. Sgouros[12], S.O. Solakcı[6], V. Soukeras[12], G. Souliotis[12], A. Spatafora[1,2], D. Torresi[1], S. Tudisco[1], A. Yildirim[6], V.A.B. Zagatto[8] for the NUMEN collaboration

[1] INFN-Laboratori Nazionali del Sud, Catania, Italy
[2] Università degli Studi di Catania, Catania, Italy
[3] UniversidadNacionalAutònoma de México, Ciudad de México, Mexico
[4] INFN-Sezione di Catania, Catania, Italy
[5] Universidade de Sao Paulo, Sao Paulo, Brazil
[6] AkdenizUniversity, Antalya, Turkey
[7] INFN-Sezione di Torino, Turin, Italy
[8] Universidade Federal Fluminense, Niteroi, Brazil
[9] Istitute of Natural Science, KaradenizTeknikUniversitesi, Trabzon, Turkey
[10] Politecnico di Torino, Turin, Italy
[11] Università di Enna "Kore", Enna, Italy
[12] University of Ioannina, Ioannina, Greece

agodi@lns.infn.it

Abstract
NUMEN proposes cross sections measurements of Heavy-Ion double charge exchange reactions as an innovative tool to access the nuclear matrix elements, entering the expression of the life time of Neutrinoless double beta decay ($0\nu\beta\beta$). A key aspect of the projectis the use at INFN-Laboratori Nazionali del Sud (LNS) of the Superconducting Cyclotron (CS) for the acceleration of the required high resolution and low emittance heavy-ion beams and of MAGNEX large acceptance magnetic spectrometer for the detection of the ejectiles. The experimental measurements of double charge exchange reactions induced by heavy ions present a number of challenging aspects, since such reactions are characterized by very low cross sections. First experimental results give encouraging indication on the capability to access quantitative information towards the determination of the Nuclear Matrix Elements for $0\nu\beta\beta$ decay.

Key words: *acceleration; charge-exchange reactions; cross sections; detection; double beta decay; heavy ions; ion beams; magnetic spectrometers; nuclear matrix; resolution; superconducting cyclotrons.*

El proyecto NUMEN: reacciones de intercambio de cargas dobles de iones pesados hacia la determinación de $0\nu\beta\beta$ NME

Resumen
NUMEN propone mediciones de secciones eficaces de reacciones de intercambio de carga doble de iones pesados como una herramienta innovadora para acceder a los elementos de la matriz nuclear, entrando en la expresión del tiempo de vida de la desintegración beta doble sin neutrino ($0\nu\beta\beta$). Un aspecto clave del proyecto es el uso en INFN-Laboratori Nazionali del Sud (LNS) del ciclotrón superconductor (CS) para la aceleración de los haces de iones pesados de alta resolución y baja emitancia requeridos y del espectrómetro magnético de gran aceptación MAGNEX para la detección de los residuos eyectados. Las mediciones experimentales de reacciones de intercambio de carga doble inducidas por iones pesados presentan una serie de aspectos desafiantes, ya que tales reacciones se caracterizan por secciones eficaces muy bajas. Los primeros resultados experimentales dan una indicación alentadora sobre la capacidad de acceder a información cuantitativa para la determinación de los Elementos de la Matriz Nuclear para la descomposición de $0\nu\beta\beta$.

Palabras clave: *aceleración; reacciones de transferencia de carga; secciones eficaces; detección; desintegración doble beta; iones pesados; haces de iones; espectrómetros magnéticos; matriz nuclear; resolución; ciclotrones superconductores.*

Introduction

Neutrinoless double beta (0νββ) decay has fundamental implications on particle physics, cosmology and fundamental physics. If observed, it is considered one of the most promising ways to probe the Majorana or Dirac nature of neutrino and to have access to its effective mass. Furthermore, the observation of 0νββ would signal that the total lepton number is not conserved.

Since the 0νββ decay process involves nuclei, its analysis necessarily implies nuclear structure elements. The 0νββ decay rate can be expressedas a product of three independent factors: the phase-space factor, the nuclear matrix element (NME) and a term containing the effective neutrino masses. Thus, even if the decay rate will be measured, the knowledge of the NME is mandatory to extract information on the neutrino masses. From an updated comparison of the main NME calculations, obtained with various nuclear structure frameworks [1]-[5], there are still significant differences. In addition some assumption common to different competing calculation, like the un avoidable truncation of the many body wave-function, could cause overall systematic uncertainties.

To access quantitative information, relevant for 0νββ decay NME, the NUMEN projectproposes to use HI-DCE reactionsas a tool [6], [7], [8]. These reactions are characterized by the transfer of two charge units, leaving the mass number unchanged, and can proceed by a sequential multi nucleon transfer mechanism or by a double meson exchange.

Despite 0νββ decay and HI-DCE reactions are mediated by different interactions, they present a number of similarities. Among that, a key aspectis that the initial and final nuclear states. Moreover, the transition operators are similar, in both cases Fermi, Gamow-Teller and rank-two tensor components are present; a large linear momentum (~100 MeV/c) is available in the virtual intermediate channel; the two processes are non-local and are characterized by two vertices localized in a pair of valence nucleons; they take placein the same nuclear medium; a relevant off-shell propagation through virtual intermediate channels is present.

In this picture, first pioneering experimental results obtained at the INFN-Laboratori Nazionali del Sud in Catania, using the MAGNEX large acceptance magnetic spectrometer [9], 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. In this way NUMEN has started an experimental campaign focused on DCE reactions involving the nuclei candidates for 0νββ decay.

DCE reactions: the 'pilot' experiment

At INFN-LNS we perform the DCE reaction ^{40}Ca (^{18}O,^{18}Ne)^{40}Ar at 270 MeV, with the aim to measure accurately the cross section at zero degrees [10]. For this reason we have chosen a particularly advantageous system, using a beam of ^{18}O and a double magic target as ^{40}Ca, choosing the bombarding energy in such a way to mismatch the competing transfer reactions leading to the same final state [11]. Crucial for the main experimental challenges involved has been the use of the CS beams delivered at LNS and the use MAGNEX, a modern high resolution and large acceptance magnetic spectrometer with high resolution in energy, mass and angle [12]. This facility has been proven to be very effective for accurate nuclear structure and dynamics studies [13], [14], [15], [16], [17], [18], [19]. In this "pilot experiment" wehaveshown [10], for the first time, high resolution and statistically significant experimental data on heavy-ion double charge exchange reactions in a wide range of transferred momenta and that precious informations towards NME determination could be a tour reach.

The NUMEN Project

To move towards nuclei candidates for 0νββ decay one needs to overcome some experimental limits asitis proposed in the NUMEN project. The challenge is to measure rare events under a very high flux of heavy ions. We consider that:

a) The Q-value for DCE reactions on nuclei of interest for 0νββ is normally more negative than in the case of ^{40}Ca explored in ref. [10]. This could strongly reduce the cross section at very forward angles.
b) The (^{18}O,^{18}Ne) reaction is particularly advantageous, due to the large value of the B(GT) strengths. However, this reaction is of β+β+ kind, while most of the research on 0νββ is in the opposite side. None of the reactions of β–β– kind looks likeas 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) has smaller B(GT), so a sensible reduction of the yield is expected;
d) In some cases gas or implanted targets are 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 (about half-MeV) is not enough to separate the ground from the excited states in the final nucleus. Thus, the coincident detection of γ-rays from the de-excitation of the populated states is mandatory, but at the price of the collected yield.

In order to start a systematic exploration of all the nuclei of interest for 0νββ decay, an upgraded set-up, able to work with at least two orders of magnitude more luminosity than the present, is necessary. This goal can be achieved by a substantial change in the technologies implemented in the beam extraction [20], in the control of the beam induced radioactivity, in the detection of the ejectiles [21-25] and in the power dissipation of the thin targets [26]. In addition, the project demands for an enhancement of the maximum accepted magnetic rigidity, preserving the geometry and field uniformity of the magnetic field [27] in order to keep the high-precision of the present trajectory reconstruction. We are also investigating the possible link between the theoretical description of the 0νββ decay and DCE reactions.

Neverthless the present limits of beam power (~100 W) for the CS accelerator and acceptable rate for the MAGNEX focal plane detector (few kHz) allow us to concentrate on some few cases. In this framework, weal ready perform some tests and measurement sboth with the (^{18}O,^{18}Ne) reaction as a probe for the β+β+ like transitions and for the first time also the (^{20}Ne,^{20}O) as a probe for β–β–.

Asexample, in the reaction test: ^{116}Sn + ^{18}O at 15 MeV/A we have measure dat 0° <θlab< 10° DCEX reaction ^{116}Sn(^{18}O,^{18}Ne)^{116}Cd; CEX reaction^{116}Sn(^{18}O,^{18}F)^{116}In; 2p-transfer ^{116}Sn (^{18}O,^{20}Ne)^{114}Cd; 1p-transfer ^{116}Sn (^{18}O,^{19}F)^{115}In.

In the reaction ^{116}Cd + ^{20}Ne at 15 MeV/A we have measure dat 0° <θlab< 8°: DCEX reaction ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn; CEX reaction ^{116}Cd(^{20}Ne,^{20}F)^{116}In; 2p-transfer ^{116}Cd(^{20}Ne,^{18}O)^{118}Sn; 2n- transfer ^{116}Cd (^{20}Ne,^{22}Ne)^{114}Cd; 1p-transfer ^{116}Cd (^{20}Ne,19F) ^{117}In; 1n-transfer ^{116}Cd(^{20}Ne,^{21}Ne)^{115}Cd.

For most of the reactions studied data reduction is in progress and for the reaction ^{116}Cd + ^{20}Ne at 15 MeV/A the analysis are almost completed and there sults will be published in the next future.

Conclusions

We have shown that high resolution and statistically-significant experimental data can be measured for DCE processes and that precious information towards NME determination could be a tour reach.

On the basis of these ground-breaking achievement, NUMEN aims to go deep insight in the HI-DCE studies on nuclei of interest in 0νββ decay, both from the theoretical and the experimental point of view, looking forward at the 0νββ NME dermination, although a simple relation between DCE cross sections and ββ- decay half-lives is not trivial and needs to be explored.

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