https://doi.org/10.1051/epjconf/202430401005

Recent results on the analysis of the ^{18}O+^{48}Ti collision at 275 MeV: single charge exchange reaction

Onoufrios Sgouros[1,2,*], *Francesco* Cappuzzello[1,2], *Manuela* Cavallaro[2], *Diana* Carbone[2], *Clementina* Agodi[2], *Giuseppe A.* Brischetto[1,2], *Daniela* Calvo[3], *Efraín R.* Chávez Lomelí[4], *Irene* Ciraldo[1,2], *Giovanni* De Gregorio[5,6], *Franck* Delaunay[1,2,7], *Haris* Djapo[8], *Canel* Eke[9], *Paolo* Finocchiaro[2], *Maria* Fisichella[2], *Angela* Gargano[5], *Marcilei A.* Guazzelli[10], *Aylin* Hacisalihoglu[11], *Roberto* Linares[12], *Jesus* Lubian[12], *Nilberto H.* Medina[13], *Maurício* Moralles[14], *Josè R. B.* Oliveira[13], *Athina* Pakou[15], *Luciano* Pandola[2], *Vasileios* Soukeras[1,2], *George* Souliotis[16], *Alessandro* Spatafora[1,2], *Domenico* Torresi[2], *Aydin* Yildirim[17], and *Vinicius A. B.* Zagatto[12] for the NUMEN collaboration

[1]Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Catania, Italy
[2]INFN – Laboratori Nazionali del Sud, Catania, Italy
[3]INFN - Sezione di Torino, Torino, Italy
[4]Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[5]INFN - Sezione di Napoli, Napoli, Italy
[6]Dipartimento di Matematica e Fisica, Università della Campania "Luigi Vanvitelli", Caserta, Italy
[7]LPC Caen UMR6534, Université de Caen Normandie, ENSICAEN, CNRS/IN2P3, Caen, France
[8]Ancara University, Institute of Accelerator Technologies, Turkey
[9]Department of Mathematics and Science Education, Akdeniz University, Antalya, Turkey
[10]Centro Universitario FEI, São Bernardo do Campo, Brazil
[11]Department of Physics, Recep Tayyip Erdogan University, Rize, Turkey
[12]Instituto de Física, Universidade Federal Fluminense, Niterói, Brazil
[13]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[14]Instituto de Pesquisas Energeticas e Nucleares IPEN/CNEN, São Paulo, Brazil
[15]Department of Physics, University of Ioannina and HINP, Ioannina, Greece
[16]Department of Chemistry, University of Athens and HINP, Athens, Greece
[17]Department of Physics, Akdeniz University, Antalya, Turkey

Abstract. The present work is inherent to the NUMEN project that aims at providing data-driven information for the nuclear matrix elements of the neutrinoless double beta decay through the study of heavy-ion induced double charge exchange reactions. This is a formidable task since during a nuclear collision, the same final states may be populated through various reaction mechanisms. In this respect, understanding the degree of competition between successive nucleon transfer and charge exchange reactions is crucial for the proper description of the meson-exchange mechanism. To this purpose, the reaction dynamics in the ^{18}O+^{48}Ti collision were sought by measuring a plethora of reaction channels under the same experimental conditions. The ^{48}Ti was chosen as target since it is the daughter nucleus of ^{48}Ca in double beta decay. The relevant experiment was performed at the MAGNEX facility of INFN-LNS in Catania. In this contribution, the status of the analysis for the ^{48}Ti(^{18}O,^{18}F)^{48}Sc single charge exchange reaction will be presented.

1 Introduction

The interest of the Physics community in the neutrinoless double beta ($0\nu\beta\beta$) decay is considerable [1]. If such a decay was to be observed, it would confirm that neutrinos are their own anti-particles. Furthermore, the decay rate of this process would allow to determine the neutrino average mass, if the nuclear matrix elements (NMEs) were known with sufficient precision, but the NMEs are not experimental observables and the various theoretical models predict values for the NMEs which are consistent to each other within a factor of 3 [2]. For this purpose, more experimental data are necessary to provide the appropriate constraints for reducing such discrepancies.

On the above grounds, the NUMEN (NUclear Matrix Elements for Neutrinoless double β decay) project [3] proposes a novel experimental approach for shedding light on the nuclear aspects of $0\nu\beta\beta$ decay, through the study of heavy-ion induced double charge exchange (DCE) reactions at energies well-above the Coulomb barrier [4]. Contrary to the case of other large-scale experimental campaigns [5–8], NUMEN aims at studying all the isotopes candidates for $0\nu\beta\beta$ decay. The lightest isotope candidate for this exotic process is ^{48}Ca which decays to the ground state of ^{48}Ti [9]. In this sense, all possible information about the structure of the ^{48}Ti nucleus are important for

*e-mail: onoufrios.sgouros@lns.infn.it

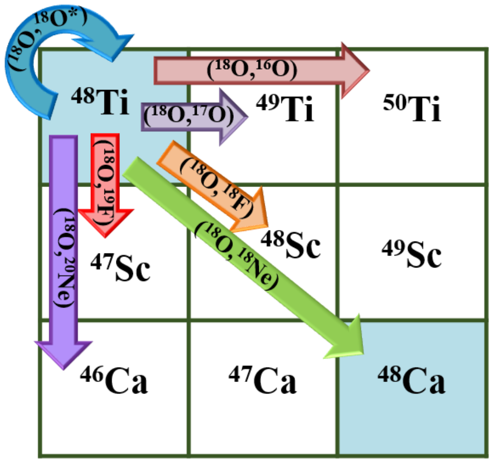

Figure 1. Nuclear reaction network measured in the ^{18}O+^{48}Ti collision at 275 MeV. Arrows indicate the reaction paths connecting the initial and final channels. The cyan curved arrow represents the elastic and inelastic scattering reactions. Figure taken from Ref. [10]

the determination of the corresponding NMEs. The choice of DCE as surrogate reactions for studying the $0\nu\beta\beta$ decay stems from the fact that, despite some differences, the two processes probe the same initial- and final-state nuclear wavefunctions [3, 11]. However, possible contributions to the measured DCE cross-section from other competing mechanisms cannot be "a priori" excluded.

In general, the DCE mechanism consists of three possible reaction modes: The direct meson-exchange DCE reaction, the double single charge exchange (DSCE) reaction [12] and the multi-nucleon transfer reactions [13–19]. All these reaction pathways may in principle populate the same final states, but only the first is connected to the $0\nu\beta\beta$ decay. Therefore, it is very important to quantify possible contributions from DSCE and/or multi-nucleon transfer to the measured DCE cross-sections [20], in order to provide with meaningful constraints on the nuclear structure theories for the description of the $0\nu\beta\beta$ decay [4, 11].

On the above grounds, in the present work which is part of the NURE project [21], the ^{18}O+^{48}Ti collision was studied by measuring in the same experiment the DCE reaction together with all competing processes. Furthermore, the study of elastic and inelastic scattering channels was performed for determining the initial state interaction [22]. A photo of the complete reaction network investigated in the present experimental campaign is shown in Figure 1. This contribution provides for the first time an overview of the analysis of the ^{48}Ti(^{18}O,^{18}F)^{48}Sc single charge exchange reaction (SCE). The analyses of elastic scattering [22] and single nucleon transfer reactions [10, 23] have been already completed, while for the case of the DCE and two-nucleon transfer reactions [24] the analyses proceed in parallel to the present one.

2 Experimental details

The experiment was conducted at the MAGNEX facility [25] of the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) in Catania. The ^{18}O^{8+} ion beam of 275 MeV was provided by the K800 Superconducting Cyclotron and bombarded a 510 μg/cm^2 thick ^{48}Ti oxide target (TiO_2) enriched at 99.8%, which was evaporated onto a thin aluminum backing. Auxiliary measurements using a self-supporting ^{27}Al target and a WO_3 one with an aluminium backing were also repeated for subtracting background events in the spectra obtained with the TiO_2 + ^{27}Al target. The reaction products were momentum analyzed by the MAGNEX large acceptance magnetic spectrometer and identified with the Focal Plane Detector (FPD) [26]. In more details, the energy loss (ΔE_{tot}) and the horizontal position (X_{foc}) of the ions were measured by means of a proportional drift chamber, while a wall of 60 silicon detectors was used to measure the ions residual energy (E_{resid}). Using the information provided by the FPD, the particle identification (PID) is performed following the prescription reported in Ref. [27]. Figure 2 shows two representative PID spectra for the case of the ^{48}Ti(^{18}O,^{18}F)^{48}Sc SCE reaction. Adopting the ΔE-E technique the ions are discriminated in atomic number considering that the stopping power of charge particles in matter is mediated by the Bethe-Bloch formula, while in the X_{foc}-E_{resid} representation ions with different ratio m/q^2 lay on a different band, since the position of the ions along the dispersive axis of a spectrometer is related to the residual energy as:

$$X_{foc} \propto \frac{\sqrt{2mE}}{q} \tag{1}$$

with m, E and q being the mass, kinetic energy and charge state of the ion, respectively.

3 Data reduction

Having completed the identification of the SCE events, the analysis of the final space parameters was performed. In Figure 3, a typical θ_{foc}-X_{foc} correlation plot is shown. The first group of events appears in the spectrum at $X_{foc}\sim$ 0.20 m, while some intense loci are well-pronounced at $X_{foc}\sim$ 0.10 m. Since in the present experiment a TiO_2 + ^{27}Al target was used, the event distribution on the θ_{foc}-X_{foc} plot is a convolution of events coming from three different reaction channels. The identification of each reaction channel was performed by means of Monte Carlo simulations, taking into account the reaction kinematics and the spatial distribution of the dipole and quadrupole magnetic fields. A comparison between experimental and simulated spectra is shown in the right-hand panel of Figure 3. As it can be seen, the agreement between experimental and simulated data is very good suggesting the validity of the dipole and quadrupole magnetic fields which are important ingredients for the trajectory reconstruction [28]. As regards the SCE reaction on ^{48}Ti, it can be seen that the ground state (g.s.) region (i.e. cyan simulated locus) is characterized by low statistics, while the intense loci at $X_{foc}\sim$ 0.10 m are originated from the ^{16}O(^{18}O,^{18}F)^{16}N reaction.

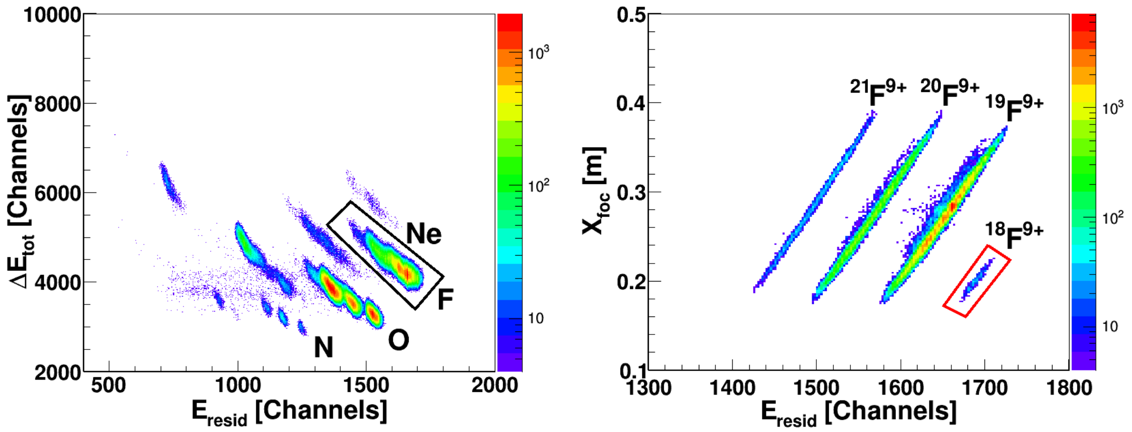

Figure 2. Particle identification for the ^{48}Ti(^{18}O,^{18}F)^{48}Sc single charge exchange reaction at 275 MeV. Left panel) A representative ΔE_{tot} - E_{resid} plot gated by one silicon detector of the FPD. The fluorine contour is highlighted with the solid black line. Right panel) A correlation plot between the horizontal position at the focal plane of the spectrometer, X_{foc}, and the E_{resid} for the identified fluorine ions of the left panel. The $^{18}F^{9+}$ events are indicated by the solid red line.

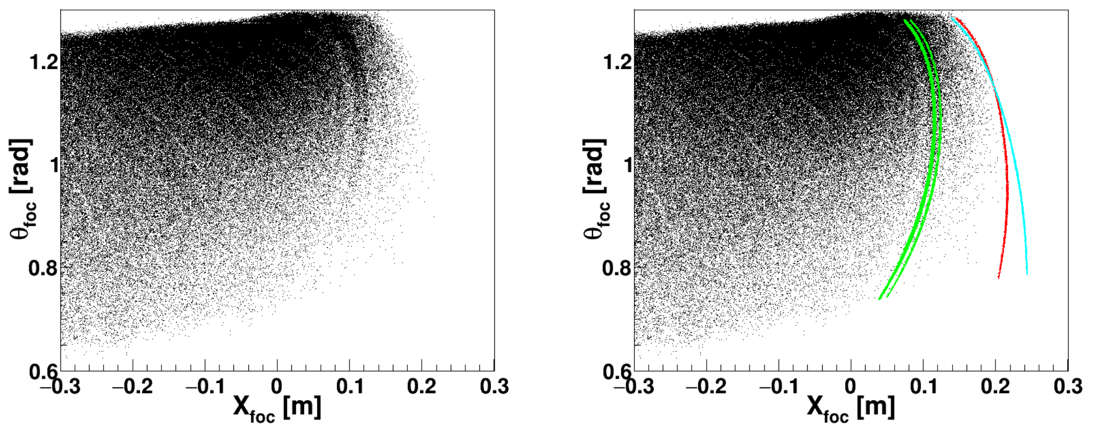

Figure 3. Left panel) Correlation plot between the horizontal angle (θ_{foc}) and position (X_{foc}) at the focal plane of MAGNEX for the identified $^{18}F^{9+}$ ions. Right panel) Comparison between experimental and simulated data in the θ_{foc}-X_{foc} representation. The red, cyan and green curves correspond to the simulated SCE events originating from the interaction of the beam with the ^{27}Al, ^{48}Ti and ^{16}O target components, respectively. For the reaction on ^{16}O, transitions to the first 4 excited states of ^{18}F ejectile were simulated while, for reasons of clarity, only the g.s. to g.s. transition was simulated for the case of the SCE reaction on ^{27}Al and ^{48}Ti.

After the determination of the dipole and quadrupole magnetic fields, a software ray reconstruction was applied to the identified data and the initial phase space parameters at the laboratory reference frame (θ_{lab}, kinetic energy) were obtained from the measured parameters at the reference frame of the focal plane (θ_{foc}, ϕ_{foc}, X_{foc}). Since the reaction we are interested in is binary one, the excitation energy, E_x, of the system was determined adopting the missing mass method [25]:

$$E_x = Q_0 - Q, \tag{2}$$

with Q_0 being the g.s. to g.s. Q-value and Q a kinematic term including the reconstructed kinetic energy of the ejectiles and the masses of the nuclei at the exit channel. The reconstructed scattering angle as a function of the excitation energy for the SCE events measured with the TiO_2 + ^{27}Al target is shown in Figure 4. As it is known, the excitation energy does not depend on the scattering angle and thus, one should expect only vertically-oriented loci for the various excited states. However, since all events were reconstructed considering the kinematics of the ^{48}Ti(^{18}O,^{18}F)^{48}Sc reaction, events coming from the reaction of the beam with the aluminum and oxygen components of the target appear as inclined loci due the difference in mass. In correspondence to Figure 3, the solid-red curve corresponds to the g.s. in the ^{27}Al(^{18}O,^{18}F)^{27}Mg reaction, while the dashed-green curve to the g.s. in the ^{16}O(^{18}O,^{18}F)^{16}N reaction. Additionally, the loci corresponding to the ground states in the reactions on aluminum and oxygen appear shifted with respect to zero, due to the difference in the Q_0 with respect to the reaction on ^{48}Ti target which is ΔQ_0= -1.4 and +6.5 MeV, respectively. The analysis of the experimental data is still ongoing. The next step includes the subtraction of the background yields using the data obtained with the self-supporting aluminum target as well as the WO_3 + ^{27}Al one and subsequently deduce the SCE energy distribution corresponding solely to the ^{48}Ti(^{18}O,^{18}F)^{48}Sc reaction.

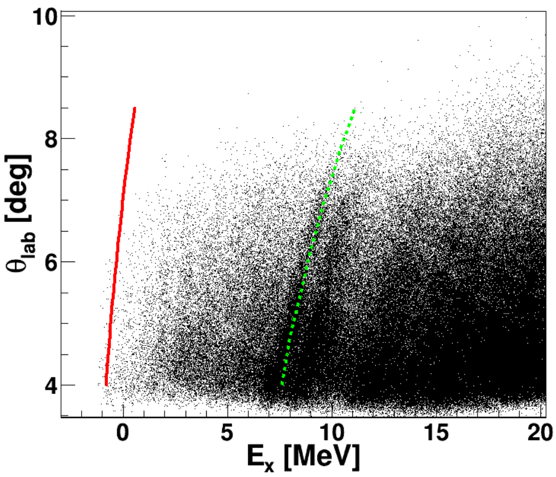

Figure 4. Preliminary reconstructed θ_{lab}-E_x correlation plot for the SCE events measured with the TiO_2 + ^{27}Al target. The inclined loci denoted with the solid-red and dashed-green curves correspond to the g.s. events from the ^{27}Al(^{18}O,^{18}F)^{27}Mg and ^{16}O(^{18}O,^{18}F)^{16}N reactions, respectively.

4 Summary

A global study of the ^{18}O+^{48}Ti collision was performed under the NUMEN and NURE experimental campaigns by measuring a wide ensemble of reaction channels. The present manuscript is dedicated to the study of the ^{48}Ti(^{18}O,^{18}F)^{48}Sc single charge exchange reaction. The experiment was conducted at INFN-LNS in Catania employing the MAGNEX large acceptance magnetic spectrometer. The $^{18}F^{9+}$ ions were well-discriminated among other reaction products by means of the ΔE-E technique in conjunction with the X_{foc}-E_{resid} plot, the latter for the isotope separation. A preliminary spectral analysis indicates low-yields for the g.s. to g.s. transition in the ^{48}Ti(^{18}O,^{18}F)^{48}Sc reaction presumably with a continuous energy distribution due to the high density of states of ^{18}F and ^{48}Sc nuclei. The latter remains to be confirmed after the subtraction of background yields is completed. The results of this analysis are important to the NUMEN project, since they will help to clarify the degree of competition between sequential and direct meson-exchange mechanisms.

Acknowledgments

This project has received financial support from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Programme (NURE - Grant agreement No. 714625).

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