IL NUOVO CIMENTO **47 C** (2024) 376
DOI 10.1393/ncc/i2024-24376-4

Colloquia: MAYORANA 2023

^{20}Ne + ^{130}Te collision in a multi-channel approach: Recent results and experimental challenges towards the NUMEN next phase

V. Soukeras(1)(2)(*), F. Cappuzzello(1)(2), D. Carbone(2), M. Cavallaro(2), C. Agodi(2), L. Acosta(3), I. Boztosun(4), G. A. Brischetto(1)(2), D. Calvo(5), E. R. Chávez Lomelí(3), I. Ciraldo(1)(2), F. Delaunay(1)(2)(6), P. Finocchiaro(2), M. Fisichella(2), A. Hacisalihoglu(2)(7), G. Lanzalone(2)(8), R. Linares(9), J. R. B. Oliveira(10), A. Pakou(11), L. Pandola(2), H. Petrascu(12), F. Pinna(5)(13), O. Sgouros(1)(2), S. O. Solakci(4), G. Souliotis(14), A. Spatafora(1)(2), D. Torresi(2), S. Tudisco(2), A. Yildirim(4) and V. A. B. Zagatto(10)
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) *Instituto de Física, Universidad Nacional Autónoma de México - Mexico City, Mexico*

(4) *Department of Physics, Akdeniz University - Antalya, Turkey*

(5) *INFN, Sezione di Torino - Torino, Italy*

(6) *LPC Caen, Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3 Caen, France*

(7) *Institute of Natural Science, Karadeniz Teknik Universitesi - Trabzon, Turkey*

(8) *Facoltà di Ingegneria e Achitettura, Università di Enna "Kore" - Enna, Italy*

(9) *Instituto de Fisica, Universidade Federal Fluminense - Niteroi, Brazil*

(10) *Instituto de Fisica, Universidade de Sao Paulo - Sao Paulo, Brazil*

(11) *Department of Physics, University of Ioannina and Hellenic Institute of Nuclear Physics Ioannina, Greece*

(12) *IFIN-HH - Bucarest, Romania*

(13) *DISAT, Politecnico di Torino - Torino, Italy*

(14) *Department of Chemistry, University of Athens and Hellenic Institute of Nuclear Physics Athens, Greece*

received 6 August 2024

(*) E-mail: `vasileios.soukeras@lns.infn.it`

Summary. — The NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project aims to access information on the neutrinoless double beta decay nuclear matrix elements through the study of the heavy-ion induced double charge exchange reactions for all $\beta\beta$ decay candidate targets. Since ^{130}Te is a candidate nucleus for $\beta\beta$ decay, the ^{20}Ne + ^{130}Te collision was experimentally investigated in a multi-channel approach by measuring the double charge exchange reaction and the complete net of reaction channels characterized by the same initial state interaction. The goal of such a study is to fully characterize the properties of the nuclear wavefunctions entering in the $0\nu\beta\beta$ decay nuclear matrix elements. The relevant experimental campaign was carried out at INFN-Laboratori Nazionali del Sud in Catania, Italy by using the Superconducting Cyclotron to accelerate the heavy ion beams and the MAGNEX magnetic spectrometer to detect the reaction ejectiles. The experimental challenges and the obtained results for the collision under study are briefly presented and discussed.

1. – Introduction

More than a century after the discovery of the atomic nucleus by Ernest Rutherford, the nuclear reaction studies have been proven to be one of the main tools for probing the nucleus properties. Among other important aspects, heavy - ion (HI) reactions may be considered as a key to unlock properties of exotic processes like the still hypothetical neutrinoless double beta ($0\nu\beta\beta$) decay [1,2]. The $0\nu\beta\beta$ is a process beyond the Standard Model, predicted a long time ago and it has the general form presented in eq. (1):

$$(1a) \qquad {}^{A_1}_{Z_1}A \rightarrow {}^{A_1}_{Z_1+2}C + 2e^- \qquad (0\nu\beta^-\beta^- decay)$$

$$(1b) \qquad {}^{A_1}_{Z_1}B \rightarrow {}^{A_1}_{Z_1-2}D + 2e^+ \qquad (0\nu\beta^+\beta^+ decay)$$

Please note that no neutrinos or antineutrinos are emitted, violating the lepton number conservation law of the Standard Model framework. Pioneering experimental campaigns aim to measure the half - life of this process for different isotopes, providing up to now only experimental lower limits [3-7]. The decay rate of the $0\nu\beta\beta$ together with a precise determination of its nuclear matrix elements (NMEs) can give access to the effective neutrino mass. The measurement of the half-life of $0\nu\beta\beta$ remains a challenging aspect however, the uncertainties met in the NMEs determination are also large, approaching a factor of 3-4 introducing an uncertainty of an order of magnitude in the effective neutrino mass [2, 8]. To this extent, it was recently proposed to use HI double charge exchange (DCE) reactions as surrogate processes for studying the $0\nu\beta\beta$ decay [9]. The general form of the DCE reactions is given in eq. (2):

$$(2a) \qquad {}^{A_0}_{Z_0}a + {}^{A_1}_{Z_1}A \rightarrow {}^{A_0}_{Z_0-2}c + {}^{A_1}_{Z_1+2}C$$

$$(2b) \qquad {}^{A_0}_{Z_0}b + {}^{A_1}_{Z_1}B \rightarrow {}^{A_0}_{Z_0+2}d + {}^{A_1}_{Z_1-2}D$$

where the nuclei A, B and C, D are those appear in eq. (1). Such reactions, although are characterized by tiny cross sections, are accessible in laboratory conditions and may provide the appropriate experimental constraints to the $0\nu\beta\beta$ NMEs.

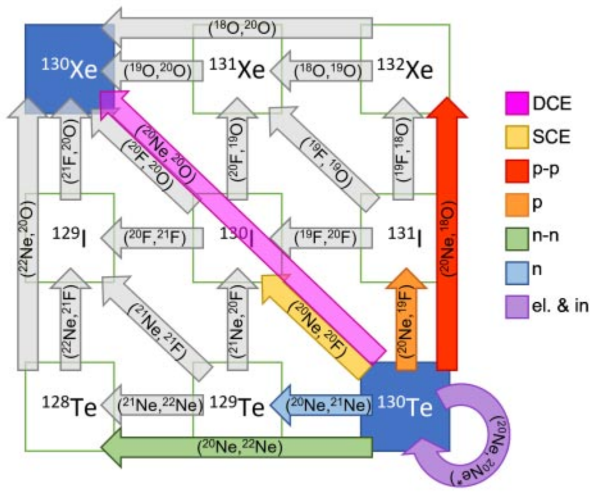

Fig. 1. – Network of possible nuclear reaction routes connecting initial and final states in the ^{20}Ne+^{130}Te collision. The measured reaction channels namely DCE, single charge exchange (SCE), one - proton transfer (p), two - proton transfer (p-p), one - neutron transfer (n), two - neutron transfer (n-n), elastic and inelastic scattering (el. & in) are presented with different colors indicated in the legend.

The NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project [9,10] aims to study the HI - induced DCE reactions on all $\beta\beta$ decay candidate targets in order to access information on the $0\nu\beta\beta$ NMEs. This is strongly motivated by a number of similarities between the two processes taking also into account that the NMEs of the two processes appeared to be in correlation [11-13]. The precise determination of the NMEs of the surrogate process requires the measurement of the DCE reaction but also, all the other reactions channels characterized by the same initial projectile and target nuclei. The net of reaction channels measured for the collision under study is presented in fig. 1.

The HI systems which were experimentally investigated so far at the beam energy of 15.3 MeV/nucleon within the NUMEN project are: ^{18}O + ^{12}C [14], ^{18}O + ^{40}Ca [15-18], ^{18}O + ^{48}Ti [19-21], ^{18}O + ^{76}Se [22-24], ^{20}Ne + ^{76}Ge [25], ^{20}Ne + ^{116}Cd [26-28] and ^{20}Ne + ^{130}Te [29-31]. The present article is dedicated to the study of the ^{20}Ne + ^{130}Te collision which was performed within the NUMEN and NURE projects [10, 32]. The ^{130}Te nucleus is investigating as $0\nu\beta\beta$ candidate in large - scale experimental searches currently taking data (*i.e.*, CUORE [3]), or under development (*i.e.*, SNO+ [33]).

2. – Experimental details and data reduction

The relevant experiment was performed at the MAGNEX facility [34] of the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. A ^{20}Ne^{10+} beam was accelerated by the K800 Superconducting Cyclotron at 306 MeV (15.3 MeV/nucleon) incident energy and impinged on a $\sim 250\ \mu$g/cm^2 ^{130}Te target evaporated onto a thin carbon foil with a thickness of $\sim 40\ \mu$g/cm^2. Two different post - stripper materials, carbon and C_3H_6 (each one in a different set of runs), were located downstream the target position in order to minimize the amount of ^{20}Ne$^{8+,9+}$

events [31]. The various ejectiles were momentum analyzed by the MAGNEX magnetic spectrometer and the different ions were detected by the MAGNEX Focal Plane Detector (FPD) [35, 36]. More experimental details may be found in refs. [29, 30, 37].

The particle identification (PID) was performed as described in ref. [38]. In particular, the PID for the reaction channels of our interest was performed by means of the standard ΔE-E technique for the ions separation based on their atomic number in conjunction with a technique for the ions mass separation which is based on the correlation between the ions kinetic energy and the measured position at the FPD. For all the cases of interest, both atomic number and mass resolution allows for the unambiguous selection of the reaction ejectiles of interest. Relevant PID spectra may be found in ref. [37]. Having identified the reaction channels of interest, a software high - order (10^{th}) ray reconstruction is applied to the selected data [39] and, the excitation energy spectra are obtained by missing mass technique, using relativistic kinematics relations for binary reactions. Finally, the absolute cross sections are extracted for each of the reaction channels of interest.

3. – Experimental results

The excitation energy spectrum for the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction, shown in fig. 2 [30], allows for the determination of the $^{130}\mathrm{Te}_{g.s.} \rightarrow {}^{130}\mathrm{Xe}_{g.s.}(0^+)$ DCE cross section (13^{+5}_{-10} nb in a 95% confidence level). The integral refers to the angular range $0.0° \leq \theta_{lab} \leq 9.5°$ and to the energy range -1 MeV $\leq E_x \leq$ 1 MeV [30] which may contain a contribution due to the transition to the $^{20}\mathrm{O}_{g.s.}(0^+)$ + $^{130}\mathrm{Xe}_{0.536}(2^+)$ since the experimental energy resolution is estimated to be $\sim$ 0.5 MeV [16, 17]. It should be also underlined the absence of any spurious events in the negative E_x region while, any background due to target backing and post-stripper material is expected at $E_x > 33$ MeV due to kinematics.

The data analysis of the quasi-elastic and inelastic scattering channels is reported in ref. [29] where the quasi-elastic and inelastic scattering cross-section angular distributions were compared to theoretical calculations, presenting in overall a very good agreement among them [29]. The data analysis for the rest of the reaction channels is in progress while, a preliminary excitation energy spectrum for the two -proton transfer reaction is shown in fig. 2.

4. – Experimental challenges towards the NUMEN next phase

The requirement of 0° measurements, the high energy resolution to unambiguously identify the DCE process and the tiny cross sections are the main experimental challenges towards the deeper investigation of the ^{20}Ne + ^{130}Te collision in the NUMEN next phase. The advent of the upgrade of the LNS facilities [40-43] will allow for a significant increase of the beam intensity while the experimental setup will be able to sustain the expected high particles rate. The latter makes it necessary the implementation of modern technologies in gas and solid state detectors of MAGNEX facility, targets setup, electronics and data acquisition systems. Finally, the use of a γ - ray calorimeter together with the development of very uniform heat resistant targets will improve significantly the achieved energy resolution in experiments with HI beams at the MAGNEX facility, thus allowing to distinguish the g.s. from the excited states of ^{130}Xe.

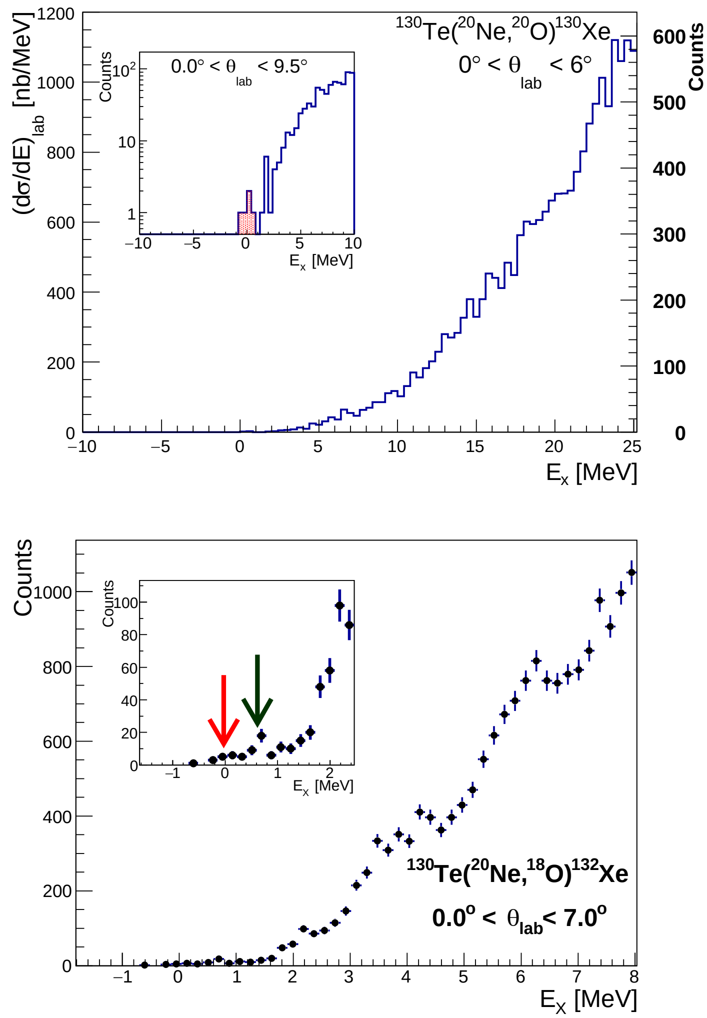

Fig. 2. – (Top panel) Excitation energy spectrum for the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction at $0.0° \leq \theta_{lab} \leq 6.0°$ angular range. A zoomed view for E$_x$ < 10 MeV and full angular range $0.0° \leq \theta_{lab} \leq 9.5°$ is shown in the inset. The red hatched area (-1 MeV $\leq E_x \leq$ 1 MeV) indicate the regions of $^{130}\mathrm{Te}_{g.s.}(0^+) \rightarrow {}^{130}\mathrm{Xe}_{g.s.}(0^+)$ and $^{130}\mathrm{Te}_{g.s.}(0^+) \rightarrow {}^{130}\mathrm{Xe}_{0.536}(2^+)$. Figure from ref. [30]. (Bottom panel) Preliminary excitation energy spectrum for the ^{130}Te(^{20}Ne,^{18}O)^{132}Xe 2p-transfer reaction at $0.0° \leq \theta_{lab} \leq 7.0°$ angular range. A zoomed view for E$_x$ < 2.5 MeV is shown in the inset while, the regions of $^{130}\mathrm{Te}_{g.s.}(0^+) \rightarrow {}^{132}\mathrm{Xe}_{g.s.}(0^+)$ and $^{130}\mathrm{Te}_{g.s.}(0^+) \rightarrow {}^{132}\mathrm{Xe}_{0.668}(2^+)$ are indicated with the red and green arrows, respectively.

* * *

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (NURE - Grant agreement No. 714625).

REFERENCES

[1] Dolinski D. J. *et al.*, *Annu. Rev. Nucl. Part. Sci.*, **69** (2019) 219.
[2] Ejiri H. *et al.*, *Phys. Rep.*, **797** (2019) 1.
[3] Adams D. Q. *et al.*, *Nature*, **604** (2022) 53.
[4] Anton G. *et al.*, *Phys. Rev. Lett.*, **123** (2019) 161802.
[5] Abe S. *et al.*, *Phys. Rev. Lett.*, **130** (2023) 051801.
[6] Agostini M. *et al.*, *Phys. Rev. Lett.*, **125** (2020) 252502.
[7] Cattadori C. M. and Salamida F., *Universe*, **7** (2021) 314.
[8] Agostini M. *et al.*, *Rev. Mod. Phys.*, **95** (2023) 025002.
[9] Cappuzzello F. *et al.*, *Prog. Part. Nucl. Phys.*, **128** (2023) 103999.
[10] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **54** (2018) 72.
[11] Shimizu N. *et al.*, *Phys. Rev. Lett.*, **120** (2018) 142502.
[12] Santopinto E. *et al.*, *Phys. Rev. C*, **98** (2018) 061601(R).
[13] Lenske H. *et al.*, *Prog. Part. Nucl. Phys.*, **109** (2019) 103716.
[14] Spatafora A. *et al.*, *Phys. Rev. C*, **107** (2023) 024605.
[15] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **51** (2015) 145.
[16] Cavallaro M. *et al.*, *Front. Astron. Space Sci.*, **8** (2021) 659815.
[17] Ferreira J. L. *et al.*, *Phys. Rev. C*, **103** (2021) 054604.
[18] Calabrese S. *et al.*, *Phys. Rev. C*, **104** (2021) 064609.
[19] Sgouros O. *et al.*, *Phys. Rev. C*, **104** (2021) 034617.
[20] Sgouros O. *et al.*, *Phys. Rev. C*, **108** (2023) 044611.
[21] Brischetto G. A. *et al.*, *Phys. Rev. C*, **109** (2024) 014604.
[22] La Fauci L. *et al.*, *Phys. Rev. C*, **104** (2021) 054610.
[23] Ciraldo I. *et al.*, *Phys. Rev. C*, **105** (2022) 044607.
[24] Ciraldo I. *et al.*, *Phys. Rev. C*, **109** (2024) 024615.
[25] Spatafora A. *et al.*, *Phys. Rev. C*, **100** (2019) 034620.
[26] Calabrese S. *et al.*, *Acta Phys. Pol. B*, **49** (2018) 275.
[27] Carbone D. *et al.*, *Phys. Rev. C*, **102** (2020) 044606.
[28] Burrello S. *et al.*, *Phys. Rev. C*, **105** (2022) 024616.
[29] Carbone D. *et al.*, *Universe*, **7** (2021) 58.
[30] Soukeras V. *et al.*, *Results Phys.*, **28** (2021) 104691.
[31] Cavallaro M.*et al.*, *Results Phys.*, **13** (2019) 102191.
[32] Cavallaro M. *et al.*, *PoS*, **BORMIO2017** (2017) 015.
[33] Albanese V. *et al.*, *J. Instrum.*, **16** (2021) P08059.
[34] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **52** (2016) 167.
[35] Torresi D. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **989** (2021) 164918.
[36] Cavallaro M. *et al.*, *Eur. Phys. J. A*, **48** (2012) 59.
[37] Soukeras V. *et al.*, *J. Phys.: Conf. Ser.*, **2619** (2023) 012016.
[38] Cappuzzello F. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **621** (2010) 419.
[39] Cappuzzello F. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **638** (2011) 74.
[40] Agodi C. *et al.*, *Universe*, **7** (2021) 72.
[41] Cappuzzello F. *et al.*, *Front. Astron. Space Sci.*, **8** (2021) 668587.
[42] Cappuzzello F. *et al.*, *Int. J. Mod. Phys. A*, **36** (2021) 2130018.
[43] Finocchiaro P. *et al.*, *Universe*, **6** (2020) 129.