Experimental and theoretical multi-channel study of direct nuclear reactions: a tool to provide data driven information on the ^{76}Ge neutrino-less double-beta decay

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Abstract. The study of heavy-ions induced double charge-exchange (HI-DCE) nuclear reactions is a promising way to access data-driven information on neutrino-less double-beta decay nuclear matrix elements. In the following, particular attention is given to the (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) HI-DCE reactions as tools for $\beta^+\beta^+$ and $\beta^-\beta^-$ decays, respectively. The experiments are performed in Catania at the Laboratori Nazionali del Sud of the Istituto Nazionale di Fisica Nucleare (INFN-LNS). The MAGNEX magnetic spectrometer is used to momentum analyse the ejectiles of a large network of nuclear reactions. New preliminary experimental data for the ^{76}Se(^{18}O,^{18}F)^{76}As and ^{76}Ge(^{20}Ne,^{20}F)^{76}As single charge exchange (SCE) and for the ^{76}Se(^{18}O,^{18}Ne)^{76}Ge and ^{76}Ge(^{20}Ne,^{20}O)^{76}Se DCE nuclear reactions were also investigated.

Neutrino-less double-beta decay is considered the *experimentum crucis* to reveal the Majorana nature of neutrinos and the lepton-number violation, being a link between the current and next-generation physics beyond the standard model [1]. The role of nuclear matrix elements (NMEs) in $0\nu\beta\beta$ research is crucial to design the next-generation experiments and to access the neutrino effective mass, if the process will be actually observed [2]. Due to that, the present spread in the results of about a factor of three for the NMEs calculated among different nuclear structure theories need to be overcome [3]. In order to constraint the NMEs values, experiments adopting a broad variety of nuclear probes have been performed in the past decades [2]. Although interesting, all these measurements revealed to be still not conclusive for the $0\nu\beta\beta$-decay NMEs.

Heavy-ion Double Charge-Exchange reactions (HI-DCE) have been recently proposed to stimulate in the laboratory the same g.s. to g.s. nuclear transition occurring in the $0\nu\beta\beta$-decay and to access the nuclear response to the second order isospin operator, in analogy to the $0\nu\beta\beta$-decay second order weak process. This analogy is the *leitmotiv* of the NUMEN (Nuclear Matrix Elements for neutrino-less double-beta decay) and NURE projects [4, 5, 6, 7, 8] proposing the idea to constrain the NMEs calculations using a new data-driven approach, based on the study of HI-DCE reactions. Promising results regarding the possibility to extract the DCE NME from the experimental cross-section measurements have been achieved in the last few years [9]. Recently, the linear correlation between the DCE double Gamow-Teller (DGT) NMEs and the $0\nu\beta\beta$ DGT and total NMEs was demonstrated using both the interacting-boson model and the large-scale shell-model nuclear structure approaches [10].

The NUMEN project aims to study the (^{18}O,^{18}Ne) DCE reaction as a probe for the $\beta^+\beta^+$ transitions and the (^{20}Ne,^{20}O) one for the $\beta^-\beta^-$, with the aim to explore the DCE mechanism in both directions [7, 9]. Since NMEs are *time invariant* quantities, they are common to a DCE and to its inverse, so the contextual measurements of both directions in the DCE represent a useful test of the procedure to extract NME from the measured DCE cross-section. The hard task to extract the NMEs from the DCE cross-section measurements could be accomplished provided that the complete description of the DCE reaction mechanism is completely under control [9]. From the experimental side, the full understanding of all the nuclear structure and reaction properties makes it necessary to study a wide network of reaction channels including the elastic and inelastic scattering [11, 12, 13], the one and two-nucleon transfer[14, 15, 16, 17, 18], the SCE [19, 20] and DCE [21, 22] nuclear reactions.

The newly proposed multi-channel approach can be applied to the study of the $\beta\beta$-decay candidates. During the conference, new experimental data and the relative theoretical analysis were presented for the networks of nuclear reactions involving the ^{76}Ge $\leftrightarrow$ ^{76}Se $\beta\beta$-decay partners. In particular, the elastic and inelastic scattering, the SCE and the DCE nuclear reaction channels.

The ^{18}O + ^{76}Se and the ^{20}Ne + ^{76}Ge collisions at 15.3 AMeV incident energy were performed at the LNS-INFN using the ^{18}O^{8+} and the ^{20}Ne^{10+} beams accelerated by the K800 Superconducting Cyclotron. The beam ions impinged on the ^{76}Se and ^{76}Ge targets evaporated

Table 1. Main parameters characterizing the experimental set-up of each explored reaction channel: target, and carbon backing thicknesses, covered scattering angles $[\theta_{lab}^{min};\theta_{lab}^{max}]$, MAGNEX central angle θ_{opt}, magnetic rigidity Bρ, quadrupole field BQ and MAGNEX solid angle acceptance are given.

	target (μg/cm^2)	C backing (μg/cm^2)	$[\theta_{lab}^{min};\theta_{lab}^{max}]$ (deg)	θ_{opt} (deg)	Bρ (Tm)	BQ (T)	Ω (msr)
^{76}Se(^{18}O,^{18}O)^{76}Se	280 ± 15	80 ± 4	[3.0; 18.5]	8.0 8.0 14.0 18.0	1.1968	-0.6638	49.2 35.0 49.2 49.2
^{76}Se(^{18}O,^{18}F)^{76}As	280 ± 15	80 ± 4	[3.0; 14.0]	8.0	1.1495	-0.6220	13.6
^{76}Se(^{18}O,^{18}Ne)^{76}Ge	280 ± 15	80 ± 4	[0.0; 9.0]	3.0	1.0086	-0.5482	10.4
^{76}Ge(^{20}Ne,^{20}Ne)^{76}Ge	390 ± 20	56 ± 3	[3.0; 20.0]	8.0 8.0 13.0 16.0 19.0	1.1397	-0.6805	49.2 32.0 49.2 49.2 49.2
^{76}Ge(^{20}Ne,^{20}F)^{76}As	390 ± 20	56 ± 3	[3.0; 14.0]	8.0	1.2270	-0.6286	1.6
^{76}Ge(^{20}Ne,^{20}O)^{76}Se	390 ± 20	56 ± 3	[0.0; 9.0]	-3.0	1.3761	-0.8175	49.2

on $^{\rm nat}$C backing layers and located in the object point of the MAGNEX magnetic spectrometer [23, 24, 25, 26], inside its scattering chamber. The ejectiles were momentum analysed in different runs in which the optical axis of MAGNEX was oriented, compared to the beam direction, at several θ_{opt} angles. During the ^{76}Se(^{18}O,^{18}Ne)^{76}Ge and the ^{76}Ge(^{20}Ne,^{20}Ne)^{76}Se DCE reaction cross-section measurements, the MAGNEX spectrometer was placed at θ_{opt} = +3° and -3°, respectively, including zero degree in the full acceptance mode ($\simeq$ 50 msr), and the total covered angular range was $0° \leq \theta_{lab} \leq 9°$. In these configuration, the beam enters in the spectrometer acceptance and the magnetic fields guide it to a place in the focal plane region away from the detectors [27]. A Faraday cup of 0.8 cm entrance diameter and 3 cm depth, mounted 15 cm downstream of the target, was used to stop the beam and collect the charge during the non-zero degree measurements. An electron suppressor polarized at -200 V and a low noise charge integrator allowed to keep the charge collection accuracy better than 10% in all the experiment runs.

The beam current was optimized at each optical angle configuration in order to reach event rates tolerable by the focal plane detector (FPD) [28]. The magnetic fields of the dipole and quadrupole magnets were set in order to transport the ions of interest in the region of momenta covered by the FPD. The data reduction strategy includes the position calibration of the FPD, identification of the ejectiles and reconstruction of the momentum vector at the target by inversion of the transport equations following the guidelines presented in previous publications [29]. Target thicknesses, covered scattering angles, spectrometer optical angles and explored solid angles are listed in Table 1 for each of the presented reaction channels.

The accurate set-up and the advanced data reduction have allowed to produce high resolution energy spectra and angular distributions for all the analysed channels. The excitation energy E_x was calculated as the difference Q_0 - Q where the Q_0 is the ground to ground state Q-value and Q is the Q-value obtained by the missing mass technique based on relativistic kinematic transformations. E_x measured spectra are shown in Figs. 1 of Refs. [11] and [13] for the ^{18}O + ^{76}Se and ^{20}Ne + ^{76}Ge elastic and inelastic scattering at 15.3 AMeV, respectively. In these cases, the achieved energy resolution is about 0.5 MeV. Slightly better values are obtained for the other reaction channels, depending on the different energy straggling produced by the ejectile/target interaction. Absolute cross-section angular distributions were extracted for the several structures clearly visible in the spectra. Theoretical analysis is in progress and will be presented in forthcoming papers.

The new multi-channel experimental and theoretical approach was applied to a wide network of nuclear reactions involving the ^{76}Ge and ^{76}Se $\beta\beta$ decay partners. Two experiments were dedicated to this scope and many nuclear reaction channels were studied, including the ^{76}Ge $\leftrightarrow$ ^{76}Se transition populated in both directions through the (^{18}O,^{18}Ne) and the (^{20}Ne,^{20}O) DCE reactions. During the conference, the results of the study on the elastic and inelastic scattering published in Refs. [11] and [13] were discussed. The preliminary ^{76}As spectra populated in the new (^{18}O,^{18}F) and (^{20}Ne,^{20}F) heavy-ion SCE reactions' measurements were compared to the results obtained in the (d,^{2}He) and (^{3}He,t) from Refs. [30] and [31], respectively. Preliminary results on the zero-degree ^{76}Se(^{18}O,^{18}Ne)^{76}Ge and the ^{76}Ge(^{20}Ne,^{20}O)^{76}Se DCE cross-sections measurements were presented, although further theoretical investigations are needed in order to master the difficult matter of extracting a nuclear matrix element. All of these results will be published in forthcoming works including the theoretical analyses.

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References

[1] Dolinski M J, Poon A W and Rodejohann W 2019 *Annual Review of Nuclear and Particle Science* **69** 219–251 URL 10.1146/annurev-nucl-101918-023407
[2] Ejiri H, Suhonen J and Zuber K 2019 *Physics Reports* **797** 1–102 URL 10.1016/j.physrep.2018.12.001
[3] Engel J and Menéndez J 2017 *Reports on Progress in Physics* **80** 046301 URL 10.1088/1361-6633/aa5bc5
[4] Cappuzzello F *et al.* 2021 *Int. Jour. of Mod. Phys. A* **36** 2130018 URL 10.1142/S0217751X21300180
[5] Cappuzzello F *et al.* 2021 *Frontiers in Astronomy and Space Sciences* **8** 668587 URL 10.3389/fspas.2021.668587
[6] Finocchiaro P *et al.* 2020 *Universe* **6** 129 URL 10.3390/universe6090129
[7] Cappuzzello F *et al.* 2018 *European Physical Journal A* **54** 72 URL 10.1140/epja/i2018-12509-3
[8] Cavallaro M *et al.* 2017 *PoS BORMIO2017* **015** URL https://pos.sissa.it/302/015/pdf
[9] Cappuzzello F *et al.* 2023 *Prog. in Part. and Nucl. Phys.* **128** 103999 URL 10.1016/j.ppnp.2022.103999
[10] Santopinto E, García-Tecocoatzi H, Magaña Vsevolodovna R I and Ferretti J 2018 *Phys. Rev. C* **98**(6) 061601 URL 10.1103/PhysRevC.98.061601
[11] La Fauci L *et al.* 2021 *Phys. Rev. C* **104**(5) 054610 URL 10.1103/PhysRevC.104.054610
[12] Carbone D *et al.* 2021 *Universe* **7** 58 URL 10.3390/universe7030058
[13] Spatafora A *et al.* 2019 *Phys. Rev. C* **100**(3) 034620 URL 10.1103/PhysRevC.100.034620
[14] Ciraldo I *et al.* 2022 *Phys. Rev. C* **105**(4) 044607 URL 10.1103/PhysRevC.105.044607
[15] Sgouros O *et al.* 2021 *Phys. Rev. C* **104**(3) 034617 URL 10.1103/PhysRevC.104.034617
[16] Calabrese S *et al.* 2021 *Phys. Rev. C* **104**(6) 064609 URL 10.1103/PhysRevC.104.064609
[17] Ferreira J L *et al.* 2021 *Phys. Rev. C* **103**(5) 054604 URL 10.1103/PhysRevC.103.054604
[18] Carbone D *et al.* 2020 *Physical Review C* **102** 044606
[19] Burrello S *et al.* 2022 *Phys. Rev. C* **105**(2) 024616 URL 10.1103/PhysRevC.105.024616
[20] Cavallaro M *et al.* 2021 *Frontiers in Astronomy and Space Sciences* **8** 61 URL 10.3389/fspas.2021.659815
[21] Soukeras V *et al.* 2021 *Results in Physics* **28** 104691 URL 10.1016/j.rinp.2021.104691
[22] Cappuzzello F *et al.* 2015 *Eur. Phys. J.* **A51** 145
[23] Cavallaro M *et al.* 2020 *Nucl.Instr.and Meth.A* **463** 334 – 338 URL 10.1016/j.nimb.2019.04.069
[24] Calabrese S *et al.* 2020 *Nucl. Instr. and Meth. A* **980** 164500 URL 10.1016/j.nima.2020.164500
[25] Calabrese S *et al.* 2018 *Acta Phys. Polon.* **B49** 275 URL 10.5506/APhysPolB.49.275
[26] Cappuzzello F, Agodi C, Carbone D and Cavallaro M 2016 *Eur. Phys. J.* **A52** 167 URL 10.1140/epja/i2016-16167-1
[27] Cavallaro M *et al.* 2019 *Res. in Phys.* **13** 102191 URL 10.1016/j.rinp.2019.102191
[28] Torresi D *et al.* 2021 *Nucl. Instr. and Meth. A* **989** 164918 URL 10.1016/j.nima.2020.164918
[29] Carbone D 2015 *The European Physical Journal Plus* **130** 143 URL 10.1140/epjp/i2015-15143-0
[30] Grewe E W *et al.* 2008 *Phys. Rev. C* **78**(4) 044301 URL 10.1103/PhysRevC.78.044301
[31] Thies J H *et al.* 2012 *Phys. Rev. C* **86**(1) 014304 URL 10.1103/PhysRevC.86.014304