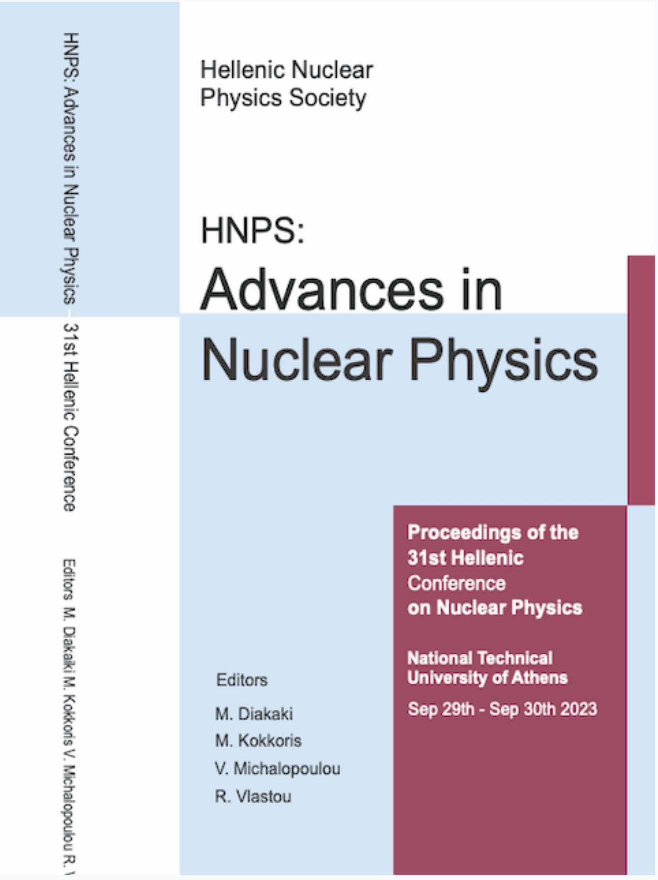
HNPS Advances in Nuclear Physics

Vol 30 (2024)

HNPS2023



Recent results in the study of the 20Ne + 130Te collision within the NUMEN project and future perspectives

Vasileios Soukeras, F. Cappuzzello, D. Carbone, M. Cavallaro, C. Agodi, L. Acosta, I. Boztosun, G. A. Brischetto, D. Calvo, E. R. Chavez – Lomeli, I. Ciraldo, F. Delaunay, P. Finocchiaro, M. Fisichella, A. Hacisalihoglu, G. Lanzalone, R. Linares, J. R. B. Oliveira, A. Pakou, L. Pandola, H. Petrascu, F. Pinna, O. Sgouros, S. O. Solakci, G. Souliotis, A. Spatafora, D. Torresi, S. Tudisco, A. Yildirim, V. A. B. Zagatto

doi: [10.12681/hnpsanp.6256](https://doi.org/10.12681/hnpsanp.6256)

Linares, R., Oliveira, J. R. B., Pakou, A., Pandola, L., Petrascu, H., Pinna, F., Sgouros, O., Solakci, S. O., Souliotis, G., Spatafora, A., Torresi, D., Tudisco, S., Yildirim, A., & Zagatto, V. A. B. (2024). Recent results in the study of the 20Ne + 130Te collision within the NUMEN project and future perspectives. *HNPS Advances in Nuclear Physics*, *30*, 154–159. https://doi.org/10.12681/hnpsanp.6256

Recent results in the study of the ^{20}Ne + ^{130}Te collision within the NUMEN project and future perspectives

V. Soukeras[1,*], F. Cappuzzello[1,2], D. Carbone[1], M. Cavallaro[1], C. Agodi[1], L. Acosta[3], I. Boztosun[4], G.A. Brischetto[1,2], D. Calvo[5], E.R. Chavez – Lomeli[3], I. Ciraldo[1,2], F. Delaunay[1,2,6], P. Finocchiaro[1], M. Fisichella[1], A. Hacisalihoglu[1,7], G. Lanzalone[1,8], R. Linares[9], J.R.B. Oliveira[10], A. Pakou[11], L. Pandola[1], H. Petrascu[12], F. Pinna[5,13], O. Sgouros[1,2], S.O. Solakci[4], G. Souliotis[14], A. Spatafora[1,2], D. Torresi[1], S. Tudisco[1], A. Yildirim[4], V.A.B. Zagatto[10] for the NUMEN collaboration

[1] *INFN – Laboratori Nazionali del Sud, Catania, Italy*
[2] *Dipartimento di Fisica e Astronomia "Ettore Majorana, Università di Catania, Catania, Italy*
[3] *Instituto di Fisica, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico*
[4] *Department of Physics, Akdeniz University, Antalya, Turkey*
[5] *INFN – Sezione di Torino, Torino, Italy*
[6] *LPC Caen, Normandie Universitè, ENSICAEN, UNICAEN, CNRS/IN2P3, Caen, France*
[7] *Institute of Natural Science, Karadeniz Teknik Universitesi, Trabzon, Turkey*
[8] *Facolta di Ingegneria e Architettura, Università di Enna "Kore", Enna, Italy*
[9] *Instituto de Fisica, Universidade Federal Fluminense, Niteroi, Brasil*
[10] *Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brasil*
[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*

Abstract The NUMEN (Nuclear Matrix Elements for Neutrinoless double beta decay) project aims to investigate specific heavy–ion double charge exchange reactions to provide experimentally data driven information about nuclear matrix elements of interest in the context of neutrinoless double beta decay (0νββ). Taking into consideration that ^{130}Te is a candidate nucleus for double beta decay, the ^{20}Ne + ^{130}Te system was experimentally investigated in a multi-channel approach by measuring the complete net of reaction channels, namely elastic and inelastic scattering, double charge exchange, single charge exchange, one– and two–nucleon transfer reactions, characterized by the same initial state interaction. The relevant experimental campaign was carried out at INFN – Laboratori Nazionali del Sud (LNS) using the Superconducting Cyclotron to accelerate the beams and the MAGNEX magnetic spectrometer to detect the reaction ejectiles. The experimental challenges and the obtained results for the ^{20}Ne + ^{130}Te system are presented and discussed. Since a deeper investigation of the ^{130}Te nucleus as well as all the nuclei which are candidates for 0νββ decay is foreseen within the next phase of NUMEN, the Research and Development activity relevant to the facility upgrade is also discussed.

Keywords heavy ions, nuclear reactions, advanced magnetic spectrometry, double charge exchange reactions, NUMEN

INTRODUCTION

Two–neutrino double beta decay (2νββ) is an exotic process predicted by M. Goeppert-Mayer a long time ago [1] and observed in a few nuclei so far. The 2νββ is a process within the Standard Model and its general form is presented in Eqn. 1.

* Corresponding author: *vasileios.soukeras@lns.infn.it*

$$
\begin{aligned}
{}^{A_1}_{Z_1}A &\rightarrow {}_{Z_1+2}^{A_1}C + 2e^- + 2\bar{\nu}_e \\
{}^{A_1}_{Z_1}B &\rightarrow {}_{Z_1-2}^{A_1}D + 2e^+ + 2\nu_e
\end{aligned} \tag{1}
$$

On the other hand, neutrinoless double beta decay (0νββ) is a hypothetical exotic process beyond the Standard Model that was predicted by E. Majorana and W. H. Furry [2,3], but not observed yet. The 0νββ follows the general form presented in Eq. 2 and may provide access to the effective neutrino mass.

$$
\begin{aligned}
{}^{A_1}_{Z_1}A &\rightarrow {}_{Z_1+2}^{A_1}C + 2e^- \\
{}^{A_1}_{Z_1}B &\rightarrow {}_{Z_1-2}^{A_1}D + 2e^+
\end{aligned} \tag{2}
$$

Since no neutrinos or antineutrinos are emitted, the 0νββ decay process violates the lepton number conservation law. To date, only experimental lower limits on the 0νββ decay rate have been deduced for some isotopes [4-8]. The decay rate of the 0νββ together with a precise determination of its nuclear matrix elements (NMEs) provide a unique tool to access the effective neutrino mass [9,10]. The extraction of beyond – the – standard model physics information from half – life measurements rely on NMEs calculations, which currently differ from each other by a factor of ~3, introducing an uncertainty of an order of magnitude in the effective neutrino mass estimation [11].

The novel idea of NUMEN [12,13] is to use nuclear reactions induced by heavy – ion accelerated beams as tools towards the determination of the ββ decay NMEs. In particular, it was proven that heavy–ion Double Charge Exchange (DCE) reactions (Eq. 3) may be considered as a surrogate process to study the 0νββ decay.

$$
\begin{aligned}
{}^{A_0}_{Z_0}a + {}^{A_1}_{Z_1}A &\rightarrow {}_{Z_0-2}^{A_0}c + {}_{Z_1+2}^{A_1}C \\
{}^{A_0}_{Z_0}b + {}^{A_1}_{Z_1}B &\rightarrow {}_{Z_0+2}^{A_0}d + {}_{Z_1-2}^{A_1}D
\end{aligned} \tag{3}
$$

where *a* and *b* are the projectile nuclei while, *A* and *B* are the target nuclei which appear also in Eqns. 1, 2.

This is strongly motivated by a number of similarities between the two processes [14-16]. A precise extraction of the NMEs of DCE reaction from the measured cross section requires also the study of all reaction channels characterized by the same initial projectile and target nuclei [15]. Therefore, NUMEN aims to experimentally investigate the complete net of reaction channels including the DCE, the Single Charge Exchange reaction (SCE), single – nucleon and two – nucleon transfer reactions, elastic and inelastic scattering channels, for all the nuclei that are 0νββ candidates and at several incident energies.

A plethora of heavy – ion collisions were investigated within the NUMEN project so far [17-34]. The focus of the present article is on the ^{20}Ne+^{130}Te collision experimentally investigated within the NUMEN [12] and NURE [35] projects providing for the first time an estimation of the DCE reaction cross section for such a heavy target. The ^{130}Te nucleus is the heaviest of the nuclei explored so far in NUMEN while the large – scale experiment CUORE [4] has provided with an experimental limit for the ^{130}Te 0νββ half-life. Finally, the SNO+ experimental campaign [36] will be able to explore the ^{130}Te as a 0νββ candidate in the near future.

EXPERIMENTAL DETAILS AND DATA REDUCTION

The relevant experiment was carried out at the MAGNEX facility [37] 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 the incident energy of 306 MeV (15.3 MeV/nucleon) and impinged on a ~250 μg/cm^2 (~1.16 x 10^{18} atoms/cm^2) ^{130}Te target evaporated onto a 40 μg/cm^2 carbon foil. Two different post – stripper materials, C_3H_6 and carbon (each one in a different set of runs), were located downstream to the target position to minimize the amount of $^{20}Ne^{8+,9+}$ elastically scattered events reaching the focal plane. A study relevant to the appropriate selection of the post – stripper materials may be found in Ref. [20].

The various ejectiles were momentum analyzed by the MAGNEX large acceptance magnetic spectrometer which is consisted of a large – aperture quadrupole magnet followed by a 55^o dipole magnet and a Focal Plane Detector (FPD) for the detection of the different ions [38,39]. The MAGNEX FPD is a hybrid detection system consisted of a gas tracker followed by a wall of 60 single silicon detectors without any intermediate foils but with only an entrance mylar window. The gas tracker includes six sections, each one having at the top a proportional wire. A set of 224 induction pads is mounted above each proportional wire allowing the measurement of the horizontal position (X_{foc}) and angle (θ_{foc}). The electron drift time measurements inside the gas allow for the determination of the vertical position (Y_{foc}) and angle (φ_{foc}). The energy loss (ΔE_{tot}) of the ions inside the gas and the residual energy (E_{resid}) are also measured by the wires and the silicon detectors, respectively. As for the ^{20}Ne + ^{130}Te collision, the double charge exchange measurement was performed at the angular range 0.0^o ≤ θ_{lab} ≤ 9.5^o. The angular coverage for the rest of the reaction channels was similar except elastic and inelastic scattering where the measurement was extended in a broader angular range by changing the spectrometer optical axis.

The particle identification (PID) was performed following the method of Ref. [40]. In particular, the first step of the PID for the reaction channels of interest is the separation of the different ions species based on their atomic number (Z) adopting the ΔE–E technique. Following the Z selection, the mass identification is feasible by a technique which is based on the correlation between the ions kinetic energy (E_{resid}) and the measured horizontal position in the FPD (X_{foc}). More details on the PID technique applied in the present study and some representative PID spectra are reported in Ref. [41]. Having identified the reaction channels of interest, a software high – order (10th) ray – reconstruction is applied to each data set [42]. The goal of such a procedure is to obtain the initial scattering parameters at the target position by using the measured parameters at the FPD (i.e. X_{foc}, Y_{foc}, θ_{foc}, φ_{foc}). The excitation energy was determined as $E_X = Q_0 – Q$, where Q_0 is the ground state to ground state Q – value and Q is the reaction Q – value adopting the missing mass method. Subsequently, the absolute cross sections were deduced for each of the reaction channels of interest.

RESULTS AND FUTURE PERSPECTIVES

The excitation energy spectrum for the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction is shown in Fig. 1 (left panel) [19]. The best estimate for the integrated cross section of the $^{130}Te_{g.s.} \rightarrow {}^{130}Xe_{g.s.}$ transition is 13^{+5}_{-10} nb (95% confidence level) in the angular range 0.0^o ≤ θ_{lab} ≤ 9.5^o and in the energy range -1 MeV ≤ E_X ≤ 1 MeV [19]. The integrated E_X region includes the transition to $^{20}O_{g.s.}(0+)$ + $^{130}Xe_{g.s.}(0+)$, but a possible contribution due to the transition to the $^{20}O_{g.s.}(0+)$ + $^{130}Xe_{0.536}(2+)$ cannot be excluded due to the finite experimental energy resolution which is ~0.5 MeV as obtained from measurements with similar experimental conditions in MAGNEX facility [24,25]. No spurious events were observed in our measurement as demonstrated by the absence of events at $E_x < 0$. It should be also mentioned that any background due to the target backing (carbon) and post-stripper material is expected at $E_x > 33$ MeV due to kinematics. The aforementioned investigation of the DCE reaction provides for the first time an estimation of the tiny DCE cross section for the $^{130}Te_{g.s.} \rightarrow {}^{130}Xe_{g.s.}$ transition which is a crucial information for the next phase of the NUMEN campaign. The ^{20}Ne + ^{130}Te collision will be revisited after the upgrade of the INFN - LNS Superconducting Cyclotron and the MAGNEX facility with higher beam intensity and at several incident energies.

The measurement of the quasi-elastic and inelastic scattering channels is reported in Ref. [18]. For both channels experimental cross-section angular distributions were deduced and compared to theoretical calculations, presenting overall a very good agreement [18]. Finally, a preliminary excitation energy spectrum for the two – proton transfer reaction is shown in Fig. 1 (right panel) [43]. In this case, the transition to the ground state of ^{132}Xe is isolated from the transition to the first excited state (E_X = 0.668 MeV). The analysis for the rest of the reaction channels is in progress.

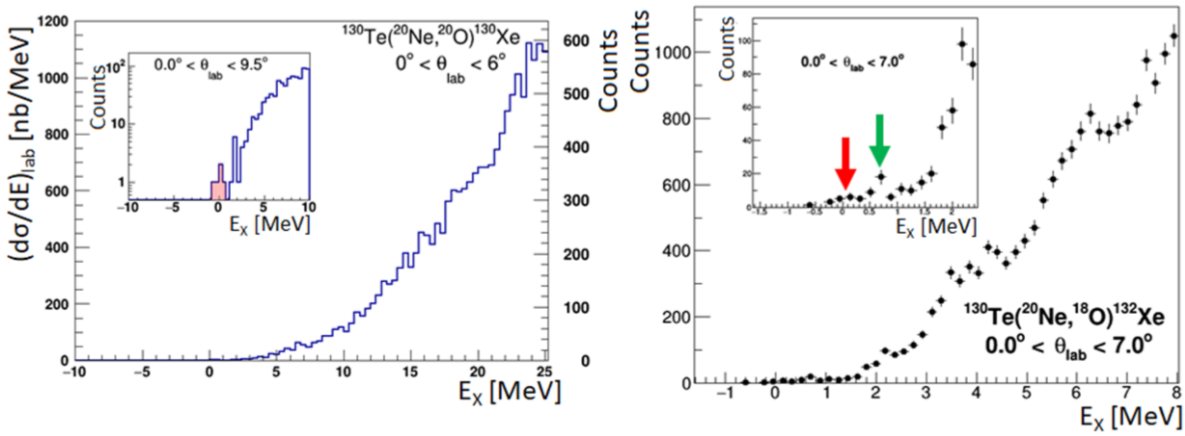


Figure 1. *(Left panel) Excitation energy spectrum for the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction at 0.0° ≤ θ_{lab} ≤ 6.0° angular range. A zoomed view for E_X < 10 MeV and angular range 0.0° ≤ θ_{lab} ≤ 9.5° is shown in the inset. The hatched area corresponds to -1 MeV ≤ E_X ≤ 1 MeV indicating the regions of $^{130}Te_{g.s.}(0+)$ → $^{130}Xe_{g.s.}(0+)$ and $^{130}Te_{g.s.}(0+)$ → $^{130}Xe_{0.536}(2+)$ transitions. Figure from Ref. [19]. (Right panel) Preliminary excitation energy spectrum for the ^{130}Te(^{20}Ne,^{18}O)^{132}Xe two – proton transfer reaction measured at the angular range 0.0° ≤ θ_{lab} ≤ 7.0°. A zoomed view for E_X < 2.5 MeV is shown in the inset while, the regions of $^{130}Te_{g.s.}(0+)$ → $^{132}Xe_{g.s.}(0+)$ and $^{130}Te_{g.s.}(0+)$ → $^{132}Xe_{0.668}(2+)$ are indicated with the red and green arrows, respectively. Figure from Ref. [43].*

With the advent of the upgraded facility, the experimental campaign will continue with a detailed investigation of all nuclei candidates for 0νββ decay at several energies. The main experimental challenges towards the deeper investigation of the ^{20}Ne + ^{130}Te collision in the next phase of NUMEN is the requirement of 0° measurements, the need of a high energy resolution in order to unambiguously identify the DCE process and the tiny cross sections of the reactions under study.

The upgrade of the Superconducting Cyclotron and in general the LNS facilities [44-47] will allow for a substantial increase of the beam intensities. In such a way we will be able to measure tiny cross sections in a reasonable time frame. Nevertheless, the experimental setup should be able to sustain the expected high particle rate. This makes necessary the implementation of modern technologies in gas and solid-state detectors of MAGNEX facility [46-48], targets setup [46,47,49,50], new electronics and data acquisition systems. The use of a γ – ray detection system (G-NUMEN) [46,47,51] together with the development of very uniform heat resistant targets [46,47,52] will improve significantly the achieved energy resolution in experiments with heavy ion beams at MAGNEX. In such a way, we should be able to unambiguously identify the DCE reaction from other processes as well as to separate the ground state to ground state transition from the transitions to excited states of the nuclei in the output channel.

SUMMARY AND CONCLUSIONS

The ^{20}Ne + ^{130}Te collision was experimentally investigated at the MAGNEX facility, in a multi-channel approach, by measuring the complete net of reaction channels, namely elastic and inelastic scattering, DCE, single charge exchange, one– and two–nucleon transfer reactions. This article provides an overview of the measurement and data reduction strategy presenting also the main findings from the analysis of the DCE reaction. The integrated cross section of the $^{130}Te_{g.s.} \rightarrow {}^{130}Xe_{g.s.}$ transition was deduced as 13^{+5}_{-10} nb in the angular range $0.0^o \leq \theta_{lab} \leq 9.5^o$ and in the energy range -1 MeV $\leq E_X \leq$ 1 MeV. Currently, a large – scale upgrade of the experimental apparatus is in progress facilitating a deeper investigation of DCE reactions for all nuclei candidates for 0νββ decay.

Acknowledgments

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] M. Goeppert-Mayer, Phys. Rev. 48, 512 (1935), doi: 10.1103/PhysRev.48.512
[2] E. Majorana, Il Nuovo Cimento 14, 171 (1937), doi: 10.1007/BF02961314
[3] W.H. Furry, Phys. Rev. 56, 1184 (1939), doi: 10.1103/PhysRev.56.1184
[4] D.Q. Adams et al., Nature 604, 53 (2022), doi: 10.1038/s41586-022-04497-4
[5] G. Anton et al., Phys. Rev. Lett. 123, 161802 (2019), doi: 10.1103/PhysRevLett.123.161802
[6] S. Abe et al., Phys. Rev. Lett. 130, 051801 (2023), doi: 10.1103/PhysRevLett.130.051801
[7] M. Agostini et al., Phys. Rev. Lett. 125, 252502 (2020), doi: 10.1103/PhysRevLett.125.252502
[8] C.M. Cattadori and F. Salamida, Universe 7, 314 (2021), doi: 10.3390/universe7090314
[9] J. Engel et al., Rep. Prog. Phys. 80, 046301 (2017), doi: 10.1088/1361-6633/aa5bc5
[10] H. Ejiri et al., Phys. Rep. 797, 1 (2019), doi: 10.1016/j.physrep.2018.12.001
[11] M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023), doi: 10.1103/RevModPhys.95.025002
[12] F. Cappuzzello et al., Eur. Phys. J. A 54, 72 (2018), doi: 10.1140/epja/i2018-12509-3
[13] F. Cappuzzello et al., Prog. Part. Nucl. Phys. 128, 103999 (2023), doi: 10.1016/j.ppnp.2022.103999
[14] N. Shimizu et al., Phys. Rev. Lett. 120, 142502 (2018), doi: 10.1103/PhysRevLett.120.142502
[15] E. Santopinto et al., Phys. Rev. C 98, 061601(R) (2018), doi: 10.1103/PhysRevC.98.061601
[16] H. Lenske et al., Prog. Part. Nucl. Phys. 109, 103716 (2019), doi: 10.1016/j.ppnp.2019.103716
[17] F. Cappuzzello et al., Eur. Phys. J. A 51, 145 (2015), doi: 10.1140/epja/i2015-15145-5
[18] D. Carbone et al., Universe 7, 58 (2021), doi: 10.3390/universe7030058
[19] V. Soukeras et al., Results in Physics 28, 104691 (2021), doi: 10.1016/j.rinp.2021.104691
[20] M. Cavallaro et al., Results in Physics 13, 102191 (2019), doi: 10.1016/j.rinp.2019.102191
[21] O. Sgouros et al., Phys. Rev. C 104, 034617 (2021), doi: 10.1103/PhysRevC.104.034617
[22] O. Sgouros et al., Phys. Rev. C 108, 044611 (2023), doi: 10.1103/PhysRevC.108.044611
[23] G.A. Brischetto et al., Phys. Rev. C 109, 014604 (2024), doi: 10.1103/PhysRevC.109.014604
[24] M. Cavallaro et al., Front. Astr. Space Sci. 8, 659815 (2021), doi: 10.3389/fspas.2021.659815
[25] J.L. Ferreira et al., Phys. Rev. C 103, 054604 (2021), doi: 10.1103/PhysRevC.103.054604
[26] S. Calabrese et al., Phys. Rev. C 104, 064609 (2021), doi: 10.1103/PhysRevC.104.064609
[27] L. La Fauci et al., Phys. Rev. C 104, 054610 (2021), doi: 10.1103/PhysRevC.104.054610
[28] I. Ciraldo et al., Phys. Rev. C 105, 044607 (2022), doi: 10.1103/PhysRevC.105.044607
[29] I. Ciraldo et al., Phys. Rev. C, accepted for publication (2024)
[30] A. Spatafora et al., Phys. Rev. C 100, 034620 (2019), doi: 10.1103/ PhysRevC.100.034620
[31] S. Calabrese et al., Acta Phys. Pol. B 49, 275 (2018), doi: 10.5506/APhysPolB.49.275
[32] D. Carbone et al., Phys. Rev. C 102, 044606 (2020), doi: 10.1103/PhysRevC.102.044606
[33] S. Burrello et al., Phys. Rev. C 105, 024616 (2022), doi: 10.1103/PhysRevC.105.024616
[34] A. Spatafora et al., Phys. Rev. C 107, 024605 (2023), doi: 10.1103/PhysRevC.107.024605
[35] M. Cavallaro et al., Proceedings of Science 302, BORMIO2017_015 (2017), doi: 10.22323/1.302.0015
[36] V. Albanese et al., Journal of Instrumentation 16, P08059 (2021), doi: 10.1088/1748-0221/16/08/P08059
[37] F. Cappuzzello et al., Eur. Phys. J. A 52, 167 (2016), doi: 10.1140/epja/i2016-16167-1
[38] D. Torresi et al., Nucl. Instr. Meth. in Phys. Res. A 989, 164918 (2021), doi: 10.1016/j.nima.2020.164918
[39] M. Cavallaro et al., Eur. Phys. J. A 48, 59 (2012), doi: 10.1140/epja/i2012-12059-8
[40] F. Cappuzzello et al., Nucl. Instr. Meth. Phys. Res. A 621, 419 (2010), doi: 10.1016/j.nima.2010.05.027
[41] V. Soukeras et al., J. Phys.: Conf. Ser. 2619, 012016 (2023), doi:10.1088/1742-6596/2619/1/012016
[42] F. Cappuzzello et al., Nucl. Instr. Meth. in Phys. Res. A 638, 74 (2011), doi: 10.1016/j.nima.2011.02.045
[43] V. Soukeras et al., MAYORANA (Multi-Aspect Young ORiented Advanced Neutrino Academy) School&Workshop, accepted for publication, Il Nuovo Cimento (2024)
[44] C. Agodi et al., Universe 7, 72 (2021), doi: 10.3390/universe7030072
[45] F. Cappuzzello et al., Front. Astr. Space Sci. 8, 668587 (2021), doi: 10.3389/fspas.2021.668587
[46] F. Cappuzzello et al., Intern. J. Mod. Phys. A 36, 2130018 (2021), doi: 10.1142/S0217751X21300180

[47] P. Finocchiaro et al., Universe 6, 12 (2020), doi: 10.3390/universe6090129
[48] I. Ciraldo et al., Nucl. Instr. Meth. Phys. Res. A 1048, 167893 (2023), doi: 10.1016/j.nima.2022.167893
[49] F. Iazzi et al., Transactions on Engineering Sciences 116, 61 (2017)
[50] V. Capirossi et al., Nucl. Instr. Meth. Phys. Res. A 954, 161122 (2018), doi: 10.1016/j.nima.2018.08.081
[51] E. M. Gandolfo et al., Instruments 7, 28 (2023), doi: 10.3390/instruments7030028
[52] M. Fisichella et al., EPJ Web of Conf. 285, 01001 (2023), doi: 10.1051/epjconf/202328501001