IL NUOVO CIMENTO **47 C** (2024) 355
DOI 10.1393/ncc/i2024-24355-9

COLLOQUIA: MAYORANA 2023

Multichannel approach for the analysis of ^{18}O + ^{40}Ca network of nuclear reactions within the NUMEN project

D. CARBONE(1)(*), C. AGODI(1), J. I. BELLONE(1), S. BURRELLO(1),
F. CAPPUZZELLO(1)(2), M. CAVALLARO(1), M. COLONNA(1), G. DE GREGORIO(3)(4),
J. L. FERREIRA(5), A. GARGANO(3), H. LENSKE(6), O. SGOUROS(1),
A. SPATAFORA(1), L. ACOSTA(7)(8), P. AMADOR-VALENZUELA(9),
G. A. BRISCHETTO(1), D. CALVO(10), E. R. CHÀVEZ LOMELÌ(7), I. CIRALDO(1),
F. DELAUNAY(11), H. DJAPO(12), C. EKE(13), P. FINOCCHIARO(1), S. FIRAT(14),
M. FISICHELLA(1), M. A. GUAZZELLI(15), A. HACISALIHOGLU(16), J. A. LAY(17)(18),
R. LINARES(5), J. LUBIAN(5), N. H. MEDINA(19), M. MORALLES(20),
J. R. B. OLIVEIRA(19), A. PAKOU(21), L. PANDOLA(1), H. PETRASCU(22),
S. O. SOLAKCI(14), V. SOUKERAS(1), G. SOULIOTIS(23), D. TORRESI(1),
S. TUDISCO(1), A. YILDIRIM(14) and V. A. B. ZAGATTO(5)
for the NUMEN Collaboration

(1) *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud - Catania, Italy*
(2) *Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania Catania, Italy*
(3) *Istituto nazionale di Fisica Nucleare, Sezione di Napoli - Napoli, Italy*
(4) *Dipartimento di Matematica e Fisica, Università della Campania "Luigi Vanvitelli" Caserta, Italy*
(5) *Instituto de Física, Universidade Federal Fluminense - Niterói, Brazil*
(6) *Department of Physics, University of Giessen - Giessen, Germany*
(7) *Instituto de Física, Universidad Nacional Autónoma de México - Mexico City, Mexico*
(8) *Istituto Nazionale di Fisica Nucleare, Sezione di Catania - Catania, Italy*
(9) *Departamento de Aceleradores y Estudio de Materiales, Instituto Nacional de Investigaciones Nucleares - Ocoyoacac, Mexico*
(10) *Istituto Nazionale di Fisica Nucleare, Sezione di Torino - Torino, Italy*
(11) *LPC Caen, Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3 Caen, France*
(12) *Institute of Accelerator Technologies, Ankara University - Ankara, Turkey*
(13) *Department of Mathematics and Science Education, Faculty of Education, Akdeniz University - Antalya, Turkey*
(14) *Department of Physics, Akdeniz University - Antalya, Turkey*
(15) *Centro Universitario FEI - São Bernardo do Campo, Brazil*
(16) *Institute of Natural Sciences, Karadeniz Teknik Universitesi - Trabzon, Turkey*
(17) *Departamento de Física Atomica, Molecular y Nuclear, Universidad de Sevilla Sevilla, Spain*
(18) *Instituto Interuniversitario Carlos I de Física Teórica y Computacional (iC1) Sevilla, Spain*
(19) *Instituto de Física, Universidade de São Paulo - São Paulo, Brazil*
(20) *Instituto de Pesquisas Energeticas e Nucleares IPEN/CNEN - São Paulo, Brazil*

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

([21]) *Department of Physics, University of Ioannina and Hellenic Institute of Nuclear Physics*
Ioannina, Greece
([22]) *Institutul National pentru Fizica si Inginerie Nucleara Horia Hulubei*
Bucarest, Romania
([23]) *Department of Chemistry, University of Athens and Hellenic Institute of Nuclear Physics*
Athens, Greece

received 6 August 2024

Summary. — A multichannel approach for the analysis of many different reactions channels induced by the ^{18}O + ^{40}Ca collisions at 275 MeV incident energy is introduced. The reactions are simultaneously measured and analysed consistently within the same reaction and structure frameworks within the NUMEN project. In particular, the elastic and inelastic scattering, one- and two-proton transfer, one-neutron transfer, and single charge exchange reactions are explored. The full quantum-mechanical calculations, performed by including microscopic nuclear structure inputs, describe well all the experimental data.

1. – Introduction

One of the most promising processes to access the effective neutrino mass and establish if it is a Mayorana particle is the neutrinoless double beta ($0\nu\beta\beta$) decay. If observed this process would have fundamental implications on particle physics, cosmology and fundamental physics. To determine quantitative information from the possible measurement of the $0\nu\beta\beta$ decay half-lives, the knowledge of the Nuclear Matrix Elements (NME) involved in the transition is mandatory [1]. In this context, the NUMEN and NURE projects [2-6] propose the use of heavy-ion induced double charge exchange (DCE) reactions as tools toward the determination of the NMEs. The basic points are that the initial and final state wave functions in the two processes are the same and the transition operators include in both cases a superposition of Fermi, Gamow-Teller and rank-two tensor components. The reaction mechanism that rules the DCE has to be fully understood in order to disentangle the reaction part from the nuclear structure aspects relevant for the $0\nu\beta\beta$ decay NMEs [7,8]. The most crucial and debated aspect in the DCE and single charge exchange (SCE) nuclear reactions is the competition between the direct process, proceeding via the meson-exchange paths, and the sequential ones proceeding through the successive transfer of nucleons [9].

The MAGNEX large acceptance magnetic spectrometer [10-13] at Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN - LNS) for high resolution measurements of the DCE reactions [14] is the essential tool to measure high resolution energy spectra and accurate cross sections at very forward angles, including zero degree, and to allow the concurrent measurement of the other relevant reaction channels (elastic and inelastic scattering [15-18], one- and two-nucleon transfer reactions [19-25] and single charge exchange [21]). A new multichannel approach has been introduced to analyze the

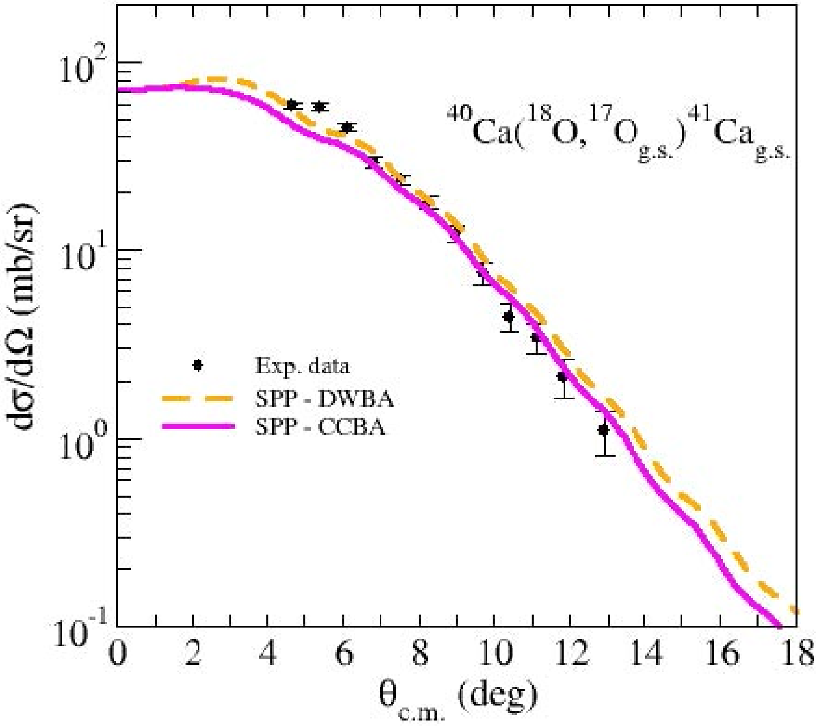

Fig. 1. – Comparison between experimental and theoretical one-neutron transfer angular distributions. No scaling factor is applied to the calculated cross sections. Cross section angular distribution for the g.s. to g.s. transition in the ^{40}Ca(^{18}O,^{17}O)^{41}Ca one-neutron transfer reaction from ref. [30]. The DWBA and CCBA calculations are shown with the dashed orange and continuous magenta curves, respectively.

experimental data of such a full net of reactions [26]. It consists in using state-of-the-art nuclear structure and reaction theories in a unique comprehensive and coherent calculation. This approach has been recently applied to analyze the net of nuclear reactions involving the ^{18}O + ^{40}Ca system at 275 MeV incident energy. In particular, here we show the results of the analysis of the elastic and inelastic scattering, one- and two-nucleon transfer, and SCE reactions.

2. – Experimental data and results

The ^{18}O + ^{40}Ca system was deeply explored by the NUMEN project, as it represented the pilot experiment performed to demonstrate the feasibility of the DCE measurements together with the complete reaction net. For the first time, high resolution and statistically significant experimental data on heavy-ion DCE reactions in a wide range of transferred momenta were measured [27], and the cross section angular distribution for the ground state (g.s.) to g.s. transition was extracted. All the concurrent reaction channels were also measured and analysed.

The experiments were perfomed at INFN-LNS using a ^{18}O beam at 275 MeV laboratory incident energy delivered by the K800 Superconducting Cyclotron. The ejectiles

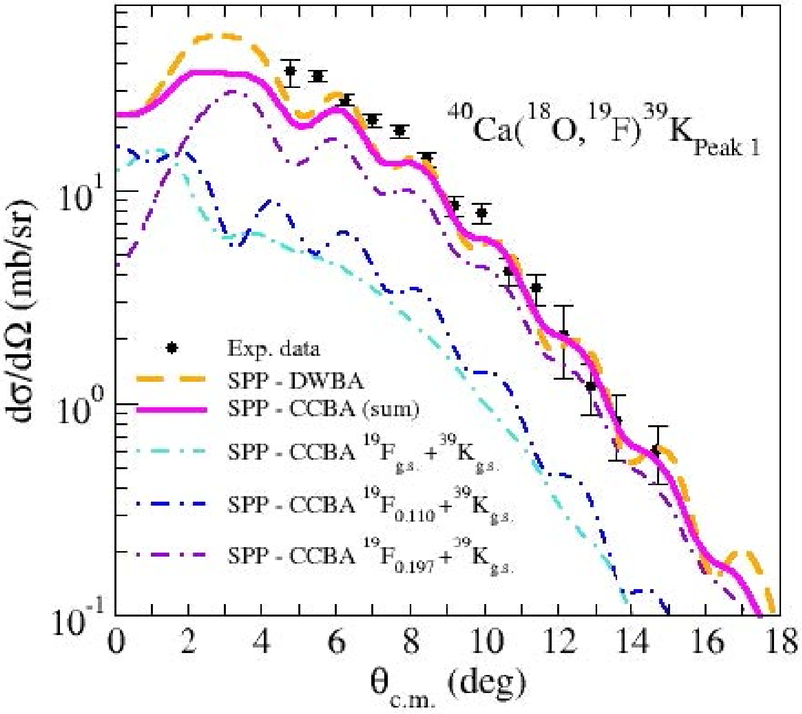

Fig. 2. – Comparison between experimental and theoretical one-proton transfer angular distributions. No scaling factor is applied to the calculated cross sections. Cross section angular distribution for the first peak observed in the ^{40}Ca(^{18}O,^{19}F)^{39}K one-proton transfer reaction of ref. [30]. The DWBA and CCBA total calculations are shown with the orange dashed and magenta continuous curves, respectively. For the CCBA calculations single-transition results are also shown by the dotted-dashed curves.

were momentum analysed by the MAGNEX magnetic spectrometer and detected by its focal plane detector [28]. Thin natural calcium targets (250 ± 12 ug/cm^2 and 280 ± 12 μg/cm^2 thick) evaporated onto a carbon backing were used. Elastic and inelastic scattering [29], one-neutron [30], one-proton [30], two-proton [31, 32] and single charge exchange [29] reactions were measured. High resolution energy spectra and absolute cross section angular distributions were extracted for the different reaction channels. Examples are shown in figs. 1 and 2, in which the one-neutron transfer and one-proton transfer cases are reported, respectively.

3. – The multichannel approach

The availability of a wide and consistent range of experimental data has allowed to apply the so called multichannel approach. From an experimental point of view, it consists in measuring the different reaction channels belonging to the same reaction net all at once in the same experimental conditions. This gives a high reliability of the measured observables, since systematic errors are largely cancelled thanks to the many available cross checks in the data. On the other hand, from a theoretical point of view, the multichannel approach allows for a constrained and reliable theoretical description of the measured data, largely reducing the need of free parameters in both nuclear structure and reaction models.

The multichannel theoretical analysis applied to the present ^{18}O + ^{40}Ca experimental data is based on full quantum-mechanical calculations with microscopic nuclear structure inputs. Fundamental ingredients are the double folding São Paulo potential as the optical potential for the initial and final state [33]. Distorted wave Born approximation (DWBA), coupled channels Born approximation (CCBA) and coupled reaction channels (CRC) approaches were used. The reaction calculations are connected to the structure of the involved nuclear states by the corresponding single- and two-particle spectroscopic amplitudes and one-body transition densities. They were derived microscopically by large-scale shell model and quasi-particle random phase approximation calculations, respectively. The calculations describe quite well all the experimental data, both in the order of magnitude and shape of the angular distributions [29-31], as visible in figs. 1 and 2, in which the ^{40}Ca(^{18}O,^{17}O)^{41}Ca one-neutron transfer and ^{40}Ca(^{18}O,^{19}F)^{39}K one-proton transfer reactions cross section angular distributions are shown, respectively.

4. – Conclusions

The multichannel approach decribed in the present paper is a powerful method to coherently analyze heavy-ion induced direct reactions. Indeed, it will be further implemented for the description of the reaction nets involving the system candidates for the neutrinoless double beta decay that will be measured in the next years within the NUMEN project.

* * *

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] Ejiri H., Suhonen J. and Zuber K., *Phys. Rep.*, **797** (2019) 1.
[2] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **54** (2018) 72.
[3] Cappuzzello F. *et al.*, *Int. J. Mod. Phys. A*, **36** (2021) 2130018.
[4] Cappuzzello F. *et al.*, *Front. Astron. Space Sci.*, **8** (2021) 668587.
[5] Finocchiaro P. *et al.*, *Universe*, **6** (2020) 129.
[6] Cavallaro M. *et al.*, *PoS*, **BORMIO2017** (2017) 015.
[7] Lenske H., Cappuzzello F., Cavallaro M. and Colonna M., *Prog. Part. Nucl. Phys.*, **109** (2019) 103716.
[8] Cappuzzello F. *et al.*, *Progr. Part. Nucl. Phys.*, **128** (2023) 103999.
[9] Ferreira J. L. *et al.*., *Phys. Rev. C*, **105** (2022) 014630.
[10] Cappuzzello F., Agodi C., Carbone D. and Cavallaro M., *Eur. Phys. J. A*, **52** (2016) 167.
[11] Cavallaro M. *et al.*, *Nucl. Instrum. Methods Phys. B*, **463** (2020) 334.
[12] Calabrese S. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **980** (2020) 164500.
[13] Calabrese S. *et al.*, *Acta Phys. Pol. B*, **49** (2018) 275.
[14] Soukeras V. *et al.*, *Results Phys.*, **28** (2021) 104691.
[15] Spatafora A. *et al.*, *Phys. Rev. C*, **100** (2019) 034620.
[16] Carbone D. *et al.*, *Universe*, **7** (2021) 58.

[17] La Fauci L. *et al.*, *Phys. Rev. C*, **104** (2021) 054610.
[18] Brischetto G. A. *et al.*, *Phys. Rev. C*, **109** (2024) 014604.
[19] Cardozo E. N. *et al.*, *Phys. Rev. C*, **97** (2018) 064611.
[20] Carbone D. *et al.*, *Phys. Rev. C*, **102** (2020) 044606.
[21] Burrello S. *et al.*, *Phys. Rev. C*, **105** (2022) 024616.
[22] Sgouros O. *et al.*, *Phys. Rev. C*, **104** (2021) 034617.
[23] Ciraldo I. *et al.*, *Phys. Rev. C*, **105** (2022) 044607.
[24] Sgouros O. *et al.*, *Phys. Rev. C*, **108** (2023) 044611.
[25] Ciraldo I. *et al.*, *Phys. Rev. C*, **109** (2024) 024615.
[26] Spatafora A. *et al.*, *Phys. Rev. C*, **107** (2023) 024605.
[27] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **51** (2015) 145.
[28] Torresi D. *et al.*, *Nucl. Instrum. Methods Phys. A*, **989** (2021) 164918.
[29] Cavallaro M. *et al.*, *Front. Astron. Space Sci.*, **8** (2021) 659815.
[30] Calabrese S. *et al.*, *Phys. Rev. C*, **104** (2021) 064609.
[31] Ferreira J. L. *et al.*., *Phys. Rev. C*, **103** (2021) 054604.
[32] Urazbekov B. *et al.*, *Phys. Rev. C*, **108** (2023) 064609.
[33] Chamon L. C. *et al.*, *Phys. Rev. Lett.*, **79** (1997) 5218.