IL NUOVO CIMENTO **49 C** (2026) 125
DOI 10.1393/ncc/i2026-26125-1

Colloquia: MAYORANA 2025

Recent results on the NUMEN analysis: The case of the ^{48}Ti(^{18}O, ^{20}Ne)^{46}Ca two-proton transfer reaction

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received 15 April 2026

Summary. — The study of the ^{18}O+^{48}Ti collision at the energy of 275 MeV was performed for the first time within the NUMEN project, where a broad network of nuclear reactions was simultaneously measured in the same experiment. Excitation energy spectra for the various reaction channels were measured employing the MAGNEX large-acceptance magnetic spectrometer. This contribution is dedicated to the study of the ^{48}Ti(^{18}O, ^{20}Ne)^{46}Ca two-proton transfer reaction.

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1. – Introduction

Neutrinos are among the most prevalent particles in the universe, however their detection remains exceptionally challenging due to their elusive nature. Therefore, some questions still remain open like whether neutrinos are their own anti-particles and what is their absolute mass scale. The most prominent probe that may provide answers to these fundamental questions is the hypothetical and yet not observed neutrino-less double β ($0\nu\beta\beta$) decay. The observation of this rare process would suggest that neutrinos are Majorana fermions, while it can give access to the absolute neutrino mass scale. The latter can be determined from a possible measurement of the $0\nu\beta\beta$ decay half-lives, if the Nuclear Matrix Elements (NMEs) involved in the transition are known with sufficient precision [1]. To this purspose, the NUMEN and NURE projects [2,3] explore heavy-ion induced double charge exchange (DCE) reactions as a mean to constrain the calculations of NMEs. The choice of DCE as probes for studying $0\nu\beta\beta$ decay stems from the fact that the initial and final state wave functions in the two processes are the same and the transition operators, introduced in the corresponding NMEs, include a superposition of Fermi, Gamow-Teller and rank-two tensor components [4-6]. In order to achieve the challenging sensitivity requested to provide experimental constraints to the $0\nu\beta\beta$ NMEs, strategies to carry out DCE cross-section measurements with high-intensity beams were developed [7]. However, in order to obtain meaningful information on the NMEs, contribution in the measured DCE cross-section from other competing processes should be quantitatively determined.

The DCE channel can be fed in principle via three different processes namely, the direct meson-exchange DCE reaction [8], the double-single charge exchange (DSCE) reaction [9] which proceeds as a sequential exchange of two uncorrelated mesons between the projectile and target and finally transfer-double charge exchange (TDCE) reaction which proceed as a sequence of multi-nucleon transfer reactions [10,11]. 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 the competition between the direct meson-exchange mechanism and the other two processes. This can be achieved by using state-of-the-art theoretical calculations [5, 11-13] for the prediction of the cross-sections for each one of the aforementioned processes, provided the appropriate experimental constraints are available. To this extent, a systematic study of transfer reactions [14-24], single charge exchange [9, 25] as well as the DCE reactions [26, 27] has been undertaken under NUMEN and NURE experimental campaigns. The related experimental results provide crucial constraints for theoretical calculations, allowing for realistic cross-section predictions for each reaction mechanism.

Apart from the challenges in the theoretical description of the DCE mechanism, the unambiguous identification of the DCE channel, the measurement of high resolution energy spectra and the accurate determination of cross-sections at very forward angles, including zero degree, is a challenging task. An example of a high performance detection system meeting all these requirements is the MAGNEX large-acceptance magnetic spectrometer [28] installed at the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) in Catania. By exploiting its large momentum acceptance, it is possible to perform simultaneous measurements of a plethora of reaction channels, like elastic and inelastic scattering, single- and two-nucleon transfer reactions together with single and double charge exchange reactions. This allows to obtain a consistent set of experimental data that can be analysed by adopting state-of-the-art nuclear structure and reaction theories in a unique and coherent calculation. So far, such a multi-channel

approach has been successfully applied for the cases of the ^{18}O+^{40}Ca and ^{18}O+^{12}C [25] collisions, while for other systems the analysis is in progress.

On the above grounds, the ^{18}O+^{48}Ti collision was studied by measuring in the same experiment the DCE reaction together with the other relevant reaction channels. The analysis of elastic and inelastic scattering [29] and single-nucleon transfer [16, 22] have been already completed, while preliminary results for the single charge exchange can be found elsewhere [30]. This contribution provides an overview of the analysis of the ^{48}Ti(^{18}O,^{20}Ne)^{46}Ca two-proton transfer reaction with emphasis on the background subtraction.

2. – Experimental setup

The experiment was conducted at the MAGNEX facility [28] of INFN-LNS in Catania. A $^{18}O^{8+}$ ion beam, accelerated to 275 MeV by the K800 Superconducting Cyclotron, impinged on a TiO_2 target with an areal density of 510 ± 20 μg/cm^2 which was evaporated onto a thin aluminum backing (216 ± 10 μg/cm^2). Supplementary measurements with a self-supporting ^{27}Al target (226 ± 10 μg/cm^2) and a WO_3 one (284 ± 15 μg/cm^2) with an aluminum backing were repeated for subtracting the background contributions from the data obtained with the TiO_2+^{27}Al target.

The various reaction ejectiles were momentum analysed by the MAGNEX large-acceptance magnetic spectrometer and were detected by its focal plane detector [31]. Data were collected for two different angular settings on the MAGNEX optical axis, namely $\theta_{opt.}$= 3^o and $\theta_{opt.}$= 9^o, allowing access to the angular range between 0^o and 15^o in the laboratory reference frame. The different ion species were identified following a technique reported in Ref. [32] and representative particle identification (PID) spectra for different reaction channels in the ^{18}O+^{48}Ti collision can be found in Refs. [16, 33].

3. – Data reduction and results

Upon completion of the PID, a high-order software ray reconstruction [34] is applied to the data using the COSY INFINITY code [35]. In this way, the momentum vector of the ion trajectories is deduced in an event-by-event basis and thus, physical quantities like scattering angle and kinetic energy can be determined. The reconstruction procedure was performed separately for the data sets obtained with the ^{27}Al, WO_3 and TiO_2+^{27}Al targets and the corresponding excitation energy was calculated as:

$$E_x = Q_0 - Q, \tag{1}$$

where Q_0 is ground state (g.s.) to g.s. Q-value and Q is the reaction Q-value calculated adopting the missing mass method [28]. An example of the excitation energy spectrum obtained with the compound titanium target is presented in fig. 1. At excitation energies beyond 2.3 MeV, events originating from the two-proton transfer reaction on the ^{27}Al backing, as well as the oxygen component of the target, are present in the spectrum. However, using the data obtained with the self-supporting ^{27}Al target and a WO_3 one, the contaminant events were subtracted from the cumulative spectrum. The background subtraction procedure is shown in fig. 2. The data obtained with ^{27}Al and WO_3 targets were appropriately normalised to account for the difference in the integrated beam charge between the different runs as well as for difference in the aluminum and oxygen scattering

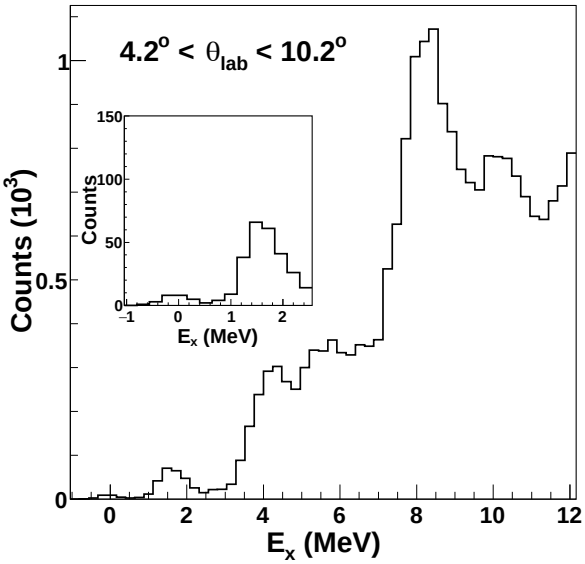


Fig. 1. – Reconstructed excitation energy spectrum for the two-proton transfer data obtained with the TiO_2+^{27}Al target. The inset shows a zoom view of the low-lying excitation energy region.

centers between the runs measured with the TiO_2+^{27}Al target and the ^{27}Al and WO_3 ones. The normalization factor of the aluminum spectrum was:

$$N^{alum.} = \frac{Q^{AL*} * T^{AL*}}{Q^{AL} * T^{AL}}, \tag{2}$$

where Q^{AL*} and T^{AL*} are the integrated beam charge and aluminum scattering centers, respectively, in the runs obtained with the TiO_2+^{27}Al target, while Q^{AL} and T^{AL} are the corresponding quantities but in the runs measured with the self-supporting ^{27}Al target. On the same footing, the normalization factor of the oxygen spectrum was evaluated as:

$$N^{oxy.} = \frac{Q^{oxy*} * T^{oxy*}}{Q^{oxy} * T^{oxy}}, \tag{3}$$

where Q^{oxy*} and T^{oxy*} are the integrated beam charge and oxygen scattering centers, respectively, in the runs with the TiO_2+^{27}Al target, while Q^{oxy} and T^{oxy} are the corresponding quantities but in the runs with the WO_3 target. As it can inferred from the inset of fig. 2, the g.s. to g.s. transition is well-separated from the second structure centered at E_x= 1.8 MeV, since the achieved energy resolution in this measurement was $\approx$ 650 keV full width at half maximum. The second structure is a convolution of the first $(2_1)^+$ states of ^{20}Ne and ^{46}Ca nuclei at 1.634 and 1.346 MeV, respectively, which could not be resolved due to the finite energy resolution. The next step of the analysis includes the determination of angular distribution cross-sections for the first two struc-

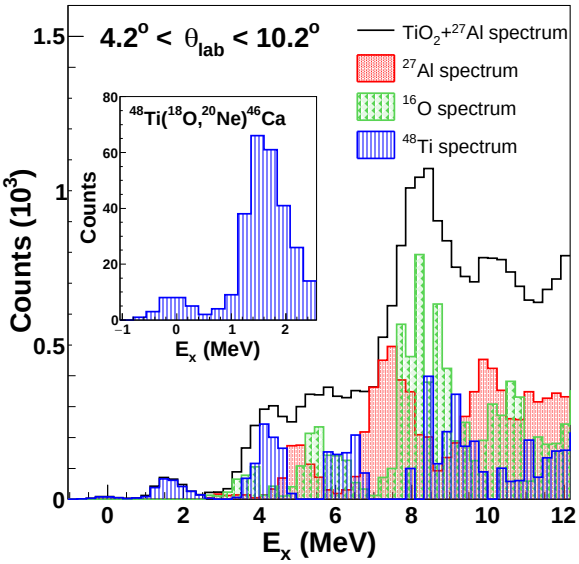


Fig. 2. – Background subtraction procedure for the two-proton transfer data obtained with the TiO_2 + ^{27}Al target. The total spectrum is depicted with the solid black line. The red-dotted area represents the normalised background spectrum originated from the reaction of the beam with the aluminum backing, while the green-filled area corresponds to the background spectrum coming from the oxygen component of the target. The spectrum in blue corresponds to the energy profile of the ^{48}Ti(^{18}O,^{20}Ne)^{46}Ca reaction, after subtracting from the cumulative spectrum the background yields. The inset shows a zoom view of the net spectrum in the low-lying excitation energy region.

tures of the excitation energy spectrum and the comparison with state-of-the-art reaction calculations to infer conclusions of the reaction mechanism mediating this process.

4. – Summary

A global study of the ^{18}O+^{48}Ti collision at 275 MeV was performed as part of the NUMEN and NURE projects by measuring a broad range of reaction observables. The present contribution is focused on the analysis of the two-proton transfer reaction, where a preliminary excitation energy spectrum was measured. Complementary measurements with a self-supporting aluminum and WO_3 + ^{27}Al targets of the appropriate thickness were performed in order to estimate the background arising from the use of a TiO_2 target evaporated onto a thin aluminum foil. After subtracting the background events, the excitation energy spectrum corresponding to the ^{48}Ti(^{18}O,^{20}Ne)^{46}Ca reaction was deduced. In the near future, angular distribution cross-sections for the low-lying excited states will be determined and analysed within in a coupled-channels framework.

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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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