

Recent results on the analysis of the $^{48}\text{Ti}(^{18}\text{O}, ^{17}\text{O})^{49}\text{Ti}$ reaction at 275 MeV

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Summary. — The study of the one-neutron transfer reaction in the $^{18}\text{O}+^{48}\text{Ti}$ collision at the energy of 275 MeV was performed as part of the multi-channel approach which is performed within the NUMEN project. That is to measure the complete reaction network characterized by the same initial and final state interactions as the more suppressed double charge exchange reactions. In this respect, angular distribution measurements for one- and two-nucleon transfer reactions in the $^{18}\text{O}+^{48}\text{Ti}$ collision were performed at the MAGNEX facility of INFN-LNS in Catania. This contribution summarizes the main findings from the analysis of the one-neutron transfer reaction.

1. – Introduction

Over the past few years, a systematic study of heavy-ion induced transfer reactions [1, 2, 3, 4, 5, 6, 7, 8, 9] has been undertaken at the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) within the NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) and NURE (NUclear REactions for neutrinoless double beta decay) projects [10, 11]. Multi-nucleon transfer reactions studies are complementary to those on double charge exchange (DCE) reactions, which have recently attracted interest due to their close analogies to the neutrinoless double β ($0\nu\beta\beta$) decay [12, 13]. In more details, multi-nucleon transfer is a competitive mechanism to the meson exchange one involved in DCE reactions, so it is very important to quantify possible contributions of sequential nucleon transfer to the measured DCE cross-sections [5], which may be the key for accessing the information on the nuclear matrix elements (NMEs) of the $0\nu\beta\beta$ decay [12, 13].

Transfer reactions are prominent spectroscopic tools since they are characterized by high selectivity in populating single-particle components of the nuclear wavefunctions [14]. Usually, the single-particle strength for a given orbital is distributed to more than one excited states in the populated nucleus, so if one can identify all the energy levels with an appreciable single-particle strength, can in principle determine the occupancy of a given orbital and subsequently compare the results to the predictions of a nuclear structure model. In this sense, transfer reactions can be used to test the shell model description of nuclei and together with the information provided by the study of DCE reactions can be used as guidelines to constrain nuclear structure theories on the NMEs of the $0\nu\beta\beta$ decay.

Taking into consideration all the above, a global study of the $^{18}\text{O}+^{48}\text{Ti}$ collision was performed by measuring a wide ensemble of reaction observables namely, elastic and inelastic scattering, one- and two-nucleon transfer reactions and single and double charge exchange reactions. The present manuscript is dedicated to the study of the $^{48}\text{Ti}(^{18}\text{O},^{17}\text{O})^{49}\text{Ti}$ one-neutron transfer reaction [9]. The analyses for some other reaction channels are still in progress [15].

2. – Experimental setup

The experiment was performed at the MAGNEX facility [16, 17] of INFN-LNS in Catania. The $^{18}\text{O}^{8+}$ ion beam was delivered by the K800 Superconducting Cyclotron at the energy of 275 MeV with an intensity of a few enA and impinged on a TiO_2 target evaporated on a thin ^{27}Al foil. Supplementary measurements with a self-supporting ^{27}Al target and a WO_3 one with an aluminium backing of the appropriate thickness were repeated, under the same experimental conditions, for subtracting the background contributions from the data obtained with the $\text{TiO}_2+^{27}\text{Al}$ target.

The various reaction ejectiles were momentum analyzed by the MAGNEX large acceptance magnetic spectrometer and were detected by its focal plane detector [18]. The optical axis of the spectrometer was set at $\theta_{\text{opt.}} = 9^\circ$ with respect to the beam axis, thus allowing us to perform angular distribution measurements of the reaction ejectiles between 3° and 15° in the laboratory reference frame. The different ion species were identified following a technique reported in Ref. [19] and representative particle identification spectra for a variety of reaction channels in the $^{18}\text{O}+^{48}\text{Ti}$ collision can be found elsewhere [3, 15, 20].

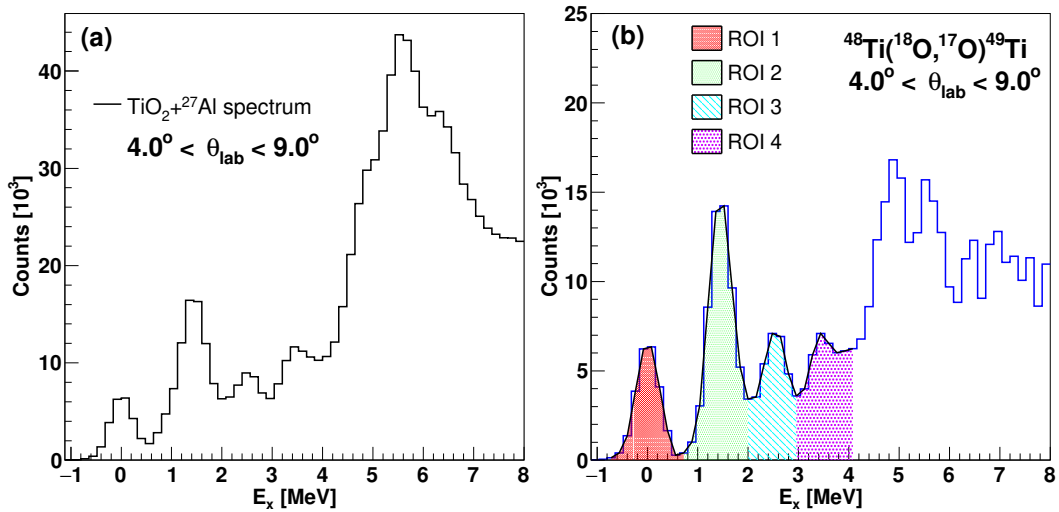


Fig. 1. – (a) Reconstructed excitation energy spectrum for the one-neutron transfer reaction at 275 MeV obtained with the $\text{TiO}_2+^{27}\text{Al}$ target. (b) Excitation energy spectrum for the $^{48}\text{Ti}(^{18}\text{O},^{17}\text{O})^{49}\text{Ti}$ reaction at 275 MeV after subtracting the background events. Figures taken from Refs. [9, 20].

3. – Data reduction and results

Having identified the $^{17}\text{O}^{8+}$ events, a high-order software ray reconstruction is applied to the data and the momentum vector of the ions at the target position is determined [21]. The reconstruction procedure was performed separately for the data sets obtained with the ^{27}Al , WO_3 and $\text{TiO}_2+^{27}\text{Al}$ targets and the corresponding excitation energy was

calculated as.

$$(1) \quad E_x = Q_0 - Q,$$

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 and assuming 2-body kinematics [16]. An example of the excitation energy spectrum obtained with the compound titanium target is presented in fig. 1a. After the $E_x > 1$ MeV events coming from the single-neutron transfer reaction on the ^{27}Al backing of the target are present in the spectrum. Contaminant events coming from the interaction of the beam with the oxygen component of the target are expected after 6 MeV. However, having in our procession the excitation energy spectrum obtained with the self-supporting ^{27}Al target and a WO_3 one, the contaminant events were subtracted and the excitation energy spectrum corresponding to the $^{48}\text{Ti}(^{18}\text{O}, ^{17}\text{O})^{49}\text{Ti}$ reaction was obtained and is shown in fig. 1b. Subsequently, by taking into account the integrated beam charge during the measurement, the scattering centers of the titanium target, the solid angle and the efficiency of the spectrometer, absolute angle-differential cross-sections were deduced. As a representative case, the differential cross-sections corresponding to ROI 3 are presented in fig. 2a.

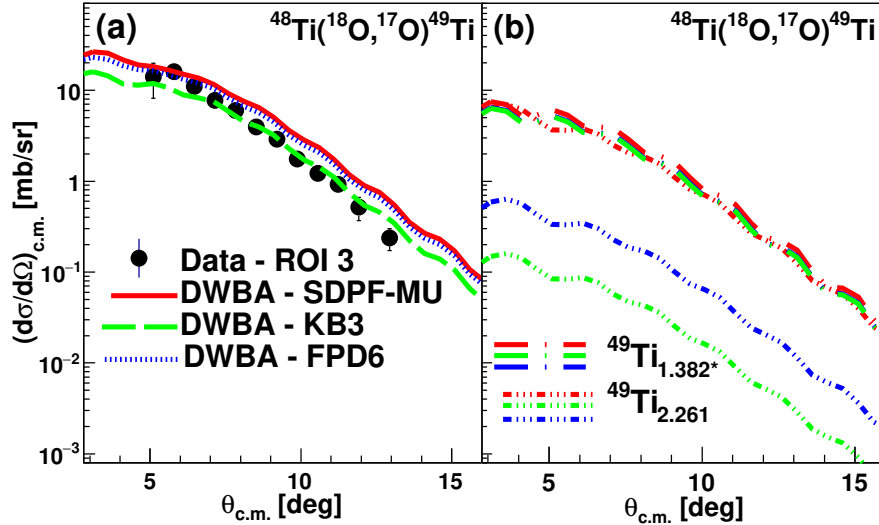


Fig. 2. – (a) Present angular distribution data for the $^{48}\text{Ti}(^{18}\text{O}, ^{17}\text{O})^{49}\text{Ti}$ reaction at 275 MeV are compared to the results of DWBA calculations. The experimental data which are indicated with the black circles correspond to the excitation energy region of fig. 1b labeled as ROI 3. The results of the DWBA calculations are illustrated with the colored curves. Each color denotes a different effective interaction used in the shell model calculations (see text for details). Figure taken from Ref. [9]. (b) Decomposition of the DWBA curves shown in panel (a), depicting the two most intense transitions. The curves are labeled by the corresponding excitation energy of ^{49}Ti nucleus with ^{17}O being in its g.s. and an asterisk when the ^{17}O is excited to the $\frac{1}{2}^+$ state at 0.871 MeV.

The angular distribution data were analyzed in a full quantum mechanical approach adopting the distorted-waves Born approximation (DWBA) reaction model using code FRESKO [22]. The differential cross-section in the DWBA approach relies on the accurate determination of the distorted waves at the entrance and exit channels as well as on the spectroscopic amplitudes. The distorted waves were calculated by solving Schrödinger equation adopting the double-folding São Paulo potential (SPP) [23] as optical potential. The SPP has been proved to describe adequately-well the elastic scattering data on various systems [24, 25, 26], while its validity to describe the elastic scattering in the $^{18}\text{O}+^{48}\text{Ti}$ collision was tested in one of our recent works [27]. The spectroscopic amplitudes, which are associated to the probability to find a valance particle (in our case the neutron) in a single-particle state coupled to a core nucleus, were computed within the framework of nuclear shell model using the code KSHELL [28]. The spectroscopic amplitudes for the $\langle ^{17}\text{O} \mid ^{18}\text{O} \rangle$ overlaps were computed employing the the p-sd-mod [29] interaction which has been successfully applied in the past to describe the structure of nuclei around the ^{16}O region [3, 4, 30]. As regards the target overlaps, the spectroscopic amplitudes were derived adopting the SDPF-MU interaction [31] as in the case of the one-proton transfer reaction [3], while tentative shell model calculations adopting the KB3 [32] and the FPD6 [33] interactions (the latter is adopted for the first time in the present work) were performed. Into this context, DWBA calculations for the $^{48}\text{Ti}(^{18}\text{O},^{17}\text{O})^{49}\text{Ti}$ reaction were performed and the results corresponding to ROI 3 are compared to the experimental data in fig. 2.

Having an inspection on fig. 2a it can be seen that the theoretical prediction adopting the SDPF-MU interaction overestimates the experimental cross-sections by a factor of ≈ 1.4 . As it is demonstrated in fig. 2b, such discrepancy is attributed equally to the large cross-sections predicted for $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states. The large cross-sections are associated to the large value for the spectroscopic amplitudes for these states, an hypothesis which is well borne out by the results of the DWBA analysis adopting the FPD6 and KB3 interactions. In these cases, smaller values for the spectroscopic amplitudes for the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states are predicted resulting to a reduction of the predicted cross-sections, especially for the case of KB3. The experimental data seem to favor the use of the KB3 interaction pointing to some deficiency of the SDPF-MU interaction in what concerns the single-neutron strength distribution for the $(\frac{5}{2}^-)_3$ state of ^{49}Ti . The complete description of the data interpretation is reported in [9].

4. – Summary

A global study of the $^{18}\text{O}+^{48}\text{Ti}$ collision at 275 MeV was performed as part of the NUMEN and NURE projects by measuring the complete net of the available direct reactions. Angular distribution measurements for the reaction ejectiles were performed at the MAGNEX facility of INFN-LNS. This work highlights the main findings from the analysis of the one-neutron transfer reaction. The experimental angular distribution cross-sections were analyzed in the DWBA framework where an appreciable sensitivity on adopted nuclear structure models was inferred. The KB3 interaction seems to be more appropriate for the description of the nuclear structure of ^{49}Ti nucleus compared to FPD6 and SDPF-MU ones. However, before precluding the validity of any interaction, systematic comparisons should be performed for all the accumulated transfer reaction data namely one-proton [3], two-proton and two-neutron transfer reaction channels.

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REFERENCES

- [1] CARBONE D. ET AL., *Phys. Rev. C*, **102** (2020) 044606
- [2] FERREIRA J. L. ET AL., *Phys. Rev. C*, **103** (2021) 054604
- [3] SGOUROS O. ET AL., *Phys. Rev. C*, **104** (2021) 034617
- [4] CALABRESE S. ET AL., *Phys. Rev. C*, **104** (2021) 064609
- [5] FERREIRA J. L. ET AL., *Phys. Rev. C*, **105** (2022) 014630
- [6] BURRELLO S. ET AL., *Phys. Rev. C*, **105** (2022) 024616
- [7] CIRALDO I. ET AL., *Phys. Rev. C*, **105** (2022) 044607
- [8] SPATAFORA A. ET AL., *Phys. Rev. C*, **107** (2023) 024605
- [9] SGOUROS O. ET AL., *Phys. Rev. C*, **108** (2023) 044611
- [10] CAPPUZZELLO F. ET AL., *Eur. Phys. J. A*, **54** (2018) 72
- [11] CAVALLARO M. ET AL., *PoS*, **BORMIO 2017** (2017) 015
- [12] LENSKE H. ET AL., *Prog. Part. Nucl. Phys.*, **109** (2019) 103716
- [13] CAPPUZZELLO F. ET AL., *Prog. Part. Nucl. Phys.*, **128** (2023) 103999
- [14] ANYAS-WEISS A. ET AL., *Phys. Rep.*, **12** (1974) 201
- [15] SGOUROS O. ET AL., *J. Phys.: Conf. Ser.*, **2586** (2023) 012034
- [16] CAPPUZZELLO F. ET AL., *Eur. Phys. J. A*, **52** (2016) 167
- [17] CAVALLARO M. ET AL., *Nucl. Instrum. Methods Phys. Res. B*, **463** (2020) 334
- [18] TORRESI D. ET AL., *Nucl. Instrum. Methods Phys. Res. A*, **989** (2021) 164918
- [19] CAPPUZZELLO F. ET AL., *Nucl. Instrum. Meth. A*, **621** (2010) 419
- [20] SGOUROS O., *Il Nuovo Cimento*, **45 C** (2022) 70
- [21] CAPPUZZELLO F. ET AL., *Nucl. Instrum. Methods Phys. Res. A*, **638** (2011) 74
- [22] THOMPSON I. J., *Comput. Phys. Rep.*, **7** (1988) 167
- [23] CANDIDO RIBEIRO M. A. ET AL., *Phys. Rev. Lett.*, **78** (1997) 3270
- [24] SPATAFORA A. ET AL., *Phys. Rev. C*, **100** (2019) 034620
- [25] CARBONE D. ET AL., *Universe*, **07** (2021) 58
- [26] LA FAUCI L. ET AL., *Phys. Rev. C*, **104** (2021) 054610
- [27] BRISCHETTO G. A. ET AL., (submitted for publication)
- [28] SHIMIZU N. ET AL., *Comput. Phys. Commun.*, **244** (2019) 372
- [29] OTSUNO Y. ET AL., *Phys. Rev. C*, **83** (2011) 021301(R)
- [30] LINARES R. ET AL., *Phys. Rev. C*, **98** (2018) 054615
- [31] OTSUNO Y. ET AL., *Phys. Rev. C*, **86** (2012) 051301(R)
- [32] POVES A. and ZUKER A., *Phys. Rep.*, **70** (1981) 235
- [33] RICHTER W. A. ET AL., *Nucl. Phys. A*, **523** (1991) 325