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The NUMEN project: probing nuclear response to weak interaction by nuclear reactions

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Abstract. Different reactions channels induced by the ^{18}O + ^{40}Ca collisions at 275 MeV incident energy are simultaneously measured and analysed consistently within the same reaction and structure frameworks within the NUMEN project. The project aims to provide data-driven information for the determination of the nuclear matrix elements involved in the neutrinoless double beta decay. 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, giving support to a multi-channel strategy for the analysis of heavy-ion induced direct reactions.

1. Introduction

The physics of neutrinoless double beta ($0\nu\beta\beta$) decay has important implications on particle physics, cosmology and fundamental physics. It is the most promising process to access the effective neutrino mass. 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]. The possibility of using heavy-ion induced double charge exchange (DCE) reactions as tools toward the determination of the NME is at the basis of the NUMEN and NURE projects [2-6]. The basic points are that the initial and final state wave functions in the two processes are the same and the transition operators are similar, including in both cases a superposition of Fermi, Gamow-Teller and rank-two tensor components. Full understanding of the DCE reaction mechanism is fundamental 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 transfer of several nucleons [9].

The availability of the MAGNEX spectrometer [10-13] at INFN-LNS for high resolution measurements of the DCE reactions [14] is essential to obtain high resolution energy spectra and accurate cross sections at very forward angles, including zero degree, and allows the concurrent measurement of the other relevant reaction channels (elastic and inelastic scattering [15-17], one- and two-nucleon transfer reactions [18-23] and single charge exchange [21]). The strategy applied to study such full net of reactions is to analyze the experimental data using state-of-the-art nuclear structure and reaction theories in a unique comprehensive and coherent calculation. This multi-channel approach has been recently applied to analyze the net of reactions involving the ^{18}O + ^{40}Ca system at 275 MeV incident energy. Here we discuss 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 represented the pilot experiment for the NUMEN project. 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 [24], allowing the extraction of the cross section angular distribution for the ground state (g.s.) to g.s. transition. Recently, the same system was explored again, in order to measure and analyse all the concurrent reaction channels. The experiments were perfomed at INFN-LNS using a ^{18}O beam accelerated at 275 MeV laboratory incident energy by the K800 Superconducting Cyclotron. The ejectiles were momentum analysed by the MAGNEX magnetic spectrometer and detected by its focal plane detector [25]. Thin natural calcium targets (250 ± 12 μg/cm^2 and 280 ± 12 μg/cm^2 thick) evaporated onto a carbon backing were used.

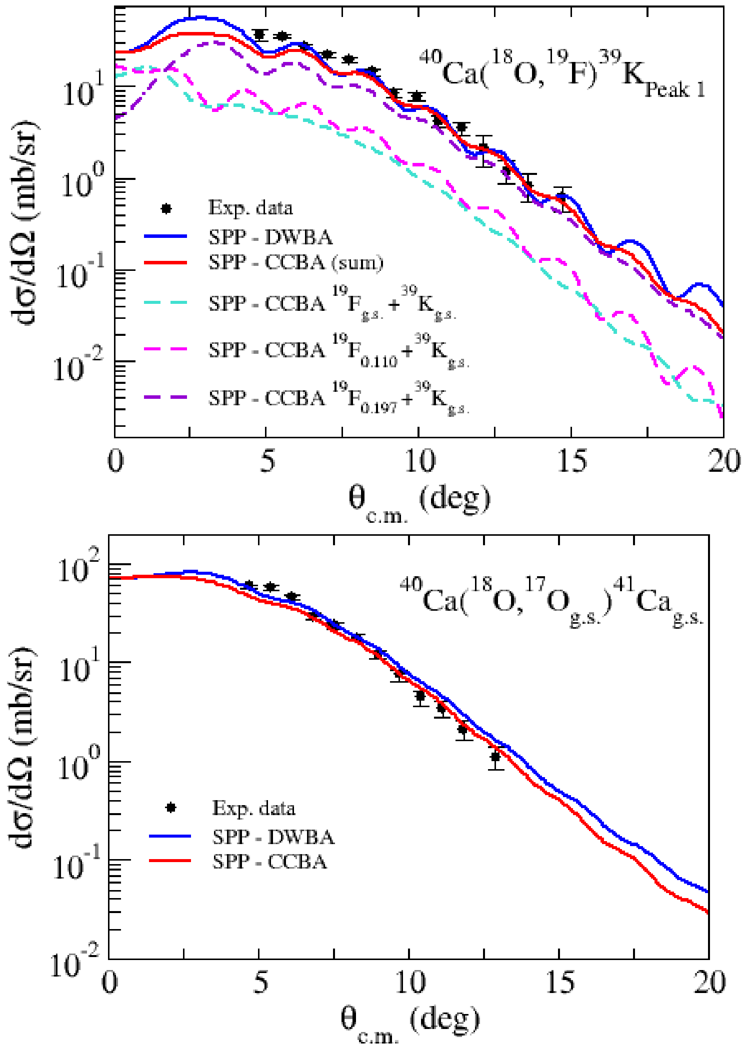

Figure 1. Comparison between theoretical and experimental one-nucleon transfer angular distributions. No scaling factor is applied to the calculated cross sections. Cross sections and angles are reported in the center of mass (c.m.) reference frame. Upper panel: Cross section angular distribution for the first peak observed in the ^{40}Ca(^{18}O,^{19}F)^{39}K one-proton transfer reaction of ref. [27]. The DWBA and CCBA total calculations are shown with the blue and red curves, respectively. For the CCBA calculations single-transition results are also shown by the dashed curves. Lower panel: 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. The DWBA and CCBA calculations are shown with the blue and red curves, respectively. From ref. [27].

Elastic and inelastic scattering [26], one-neutron [27], one-proton [27], two-proton [28] and single charge exchange [26] reactions were measured. High resolution energy spectra and absolute cross section angular distributions were extracted for the different reaction channels. The availability of such a wide and consistent range of experimental data has allowed to apply the so called “multi-channel” approach which uses a constrained and reliable theoretical description. It 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 [29]. 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. An example is reported in Figure 1, in which the ^{40}Ca(^{18}O,^{19}F)^{39}K one-proton transfer and ^{40}Ca(^{18}O,^{17}O)^{41}Ca one-neutron transfer reactions are shown.

3. Conclusions

The presented multi-channel approach is a powerful method to coherently analyze heavy-ion induced direct reactions and will be further implemented for the exploration of all the system candidates for the neutrinoless double beta decay that will be measured in the next years within the NUMEN project.

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