The multichannel approach within the NUMEN project: the ^{18}O + ^{40}Ca at 275 MeV case

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Abstract. Different reactions channels induced by the ^{18}O + ^{40}Ca collisions at 275 MeV incident energy are analysed within a a multichannel approach. Ex-

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perimental data from many reactions are simultaneously measured and a consistent analysis is performed with the same reaction and structure frameworks. The results are part of 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 experimental data are well described by the theoretical calculations, performed by including microscopic nuclear structure inputs.

1 Introduction

The neutrinoless double beta ($0\nu\beta\beta$) decay is one of the most promising processes to access the effective neutrino mass and establish if it is a Mayorana particle. The observation of this process would have fundamental implications on particle physics, cosmology and fundamental physics. However, to extract 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 understand 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 INFN-Laboratori Nazionali del Sud for high resolution measurements of the DCE reactions [14] offers the possibility to measure 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 [15–18], one- and two-nucleon transfer reactions [19–25] and single charge exchange [21]). A newly multichannel approach was introduced to analyze the 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.

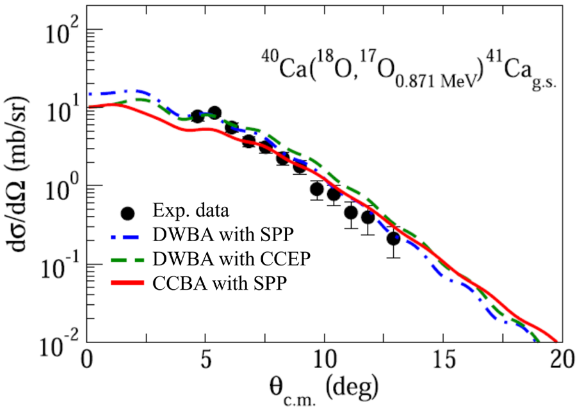

Figure 1. Comparison between experimental and theoretical one-neutron transfer angular distributions. No scaling factor is applied to the calculated cross sections. Cross section angular distribution for the $^{40}Ca(^{18}O,^{17}O_{0.871MeV})^{41}Ca_{g.s.}$ transition. Different calculations are shown: DWBA with SPP (blue dotted-dashed line), DWBA with CCEP (green dashed line) and CCBA (continuous red line) approaches. From ref. [30].

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 were momentum analysed by the MAGNEX large acceptance 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] 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, which, from an experimental point of view, consists in measuring the different reaction channels belonging to the same reaction net all at once in the same experimental conditions, thus giving a high reliability of the measured observables, since systematic errors are largely canceled 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) and coupled channels Born approximation (CCBA) were used. Regarding the nuclear structure ingredients included in the calculations, single- and two-particle spectroscopic amplitudes and one-body transition densities were derived microscopically by large-scale shell model and

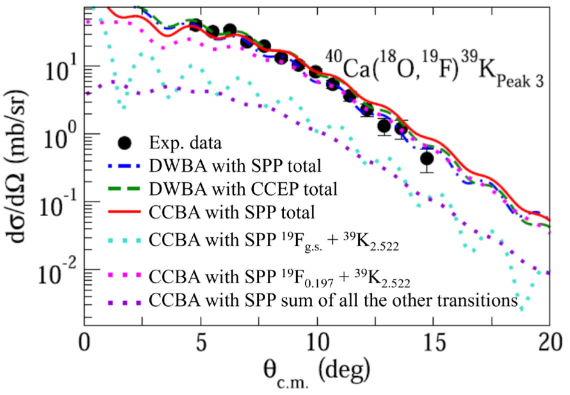

Figure 2. Comparison between experimental and theoretical one-proton transfer angular distributions. No scaling factor is applied to the calculated cross sections. Cross section angular distribution for the third peak observed in the ^{40}Ca(^{18}O,^{19}F)^{39}K one-proton transfer reaction of ref. [30]. Different calculations are shown: the sum obtained within DWBA using the SPP (blue dotted-dashed line), the sum obtained within DWBA using the CCEP (green dashed line) and the sum obtained within CCBA (continuous red line) approaches. Single transitions as well as partial sums, calculated in the CCBA approach, are reported as dotted lines. From ref. [30]

quasi-particle random phase approximation calculations, respectively. The obtained calculations are shown 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.

In some cases, we realized that couplings with the inelastic excitations of both projectile and target nuclei are needed to correctly describe the elastic channel as well as other reaction channels (e.g. inelastic or single charge exchange). However, sometimes the implementation of such CC approach is very demanding from both theoretical and computational point of views. For these reasons, we explored also the possibility to implicitly embed the effect of the inelastic excitations on the elastic channel by the use of coupled channel equivalent polaritazion potentials (CCEP). It is obtained by adding to the bare optical potential, the SPP in our case, an additive local term known as a trivially equivalent local potential (TELP) [34], which includes in an effective way the inelastic couplings among the different considered states, already in the DWBA scheme. Examples are visible in Figs. 1 and 2.

Regarding the one-neutron transfer case (Fig. 1), the DWBA calculations with SPP well describe the data in the most forward angular region, slightly overestimating them at larger angles. Similar behaviour is observed for the DWBA calculation with CCEP. The CCBA approach with SPP corresponds to a different slope which is less steep than the DWBA ones. In the one-proton transfer case, the number of the involved channels of the final partition for the transition shown in Fig. 2 is significantly largem, since both the ejectile (^{19}F) and the residual nucleus (^{39}K) may populate many possible excited states from the contributions of ten final partition channels. Nevertheless, few transitions dominate over all the others. In particular, the ^{19}F$_{0.197}$ + ^{39}K$_{2.522}$ final transition gives the largest contribution while a limited enhancement in the oscillation pattern is provided by the transition towards the ^{19}F$_{g.s.}$ + ^{39}K$_{2.522}$ final channel. The sum of all the other transitions gives a suppressed and almost constant contribution. Comparing the results obtained applying the different theoretical schemes, the DWBA with SPP is slightly smaller than the DWBA with CCEP one, providing an excellent agreement with the data in both cases. The CCBA angular distribution is instead higher than the others especially at large scattering angles, slightly overestimating the experimental result.

In general, the agreement with the experimental data is quite satisfactory both in the order of magnitude and shape of the angular distributions [29–32], validating the employed nuclear structure and reaction models and confirming that absolute agreements can be reached without the need for any arbitrary scaling. Moreover, the different adopted reaction schemes return similar results, demonstrating a substantial equivalence among the different approaches.

4 Conclusions

The multichannel approach described 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. At the start of the NUMEN project, neither reaction nor structure theory had at hand approved methods for second-order processes. In the last years, significant progresses were made in developing the appropriate theoretical formalism and the numerical methods and computer codes, enabling now the exploration of all reaction channels by using the same experimental conditions and a unique theoretical framework in the multichannel approach presented in this paper. These studies are a selective tool to acquire spectroscopic information and at the same time they allow to pinpoint and constrain the intermediate channels relevant for the population of SCE and DCE channels. In the attempt to extract the DCE cross sections and get information on the $0\nu\beta\beta$ NMEs, it is necessary to coherently combine the reaction amplitudes of transfer and direct SCE and DCE processes in order to properly account for the quantal interference effects between these competing reaction mechanisms. Recently a step forward in solving this problem has been made through the multichannel approach applied to the SCE reaction in the ^{18}O + ^{12}C system at 275 MeV incident energy in which the transfer states and the configurations reached by direct SCE transitions were described within the same large scale shell model approach [35].

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