Two-nucleon transfer and Double Charge Exchange reactions

E Santopinto, R I Magana Vsevolodovna, and H García-Tecocoatzi, within the NUMEN project
Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy
E-mail: santopinto@ge.infn.it

Abstract. In this contribution we present a study of a direct and sequential two-nucleon transfer within the microscopic Interacting Boson Model (IBM-2) and Interacting Boson-Fermion Model (IBFM), respectively. We present our preliminary results for heavy-ion double-charge-exchange $^{40}\text{Ca}(^{18}\text{O},^{18}\text{Ne})^{40}\text{Ar}_{G.S.}$ differential cross section too.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is one of the most important processes that has not been observed yet, and it represents a probe of physics beyond the Standard Model. One open problem is that the $0\nu\beta\beta$ decay depends on nuclear matrix elements (NMEs) that when evaluated using different nuclear structure models can differ also by about a factor of 2-3 [1]. A better understanding of the nuclear structure will help to improve the model calculation of nuclear reactions and decay processes, such as single beta decay, double beta decay ($2\nu\beta\beta$), and $0\nu\beta\beta$. The knowledge of the internal degrees of freedom is crucial to understand nuclear structure.

In order to calculate the competing two-nucleon processes to heavy-ion double charge exchange (DCE), recently we developed the formalism using microscopic IBM-2 for the NUMEN collaboration [2, 3, 4], and this formalism has been already applied with success to $^{64}\text{Ni}(^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$ two-neutron transfer as reported here in section 2 and 3. Finally, since our goal is to describe the DCE differential cross section using IBMs for the nuclear part, trying to extract information on NMEs of nuclei involved also in $0\nu\beta\beta$, we present here in the last section very preliminary results regarding DCE $^{40}\text{Ca}(^{18}\text{O},^{18}\text{Ne})^{40}\text{Ar}_{G.S.}$ differential cross section.

2. The $^{64}\text{Ni}(^{15}\text{O},^{16}\text{O})^{66}\text{Ni}$ two-neutron transfer

The two-neutron transfer of $^{18}\text{O}+^{64}\text{Ni}$ has been measured at the INFN- Laboratori Nazionali del Sud (Italy) using the MAGNEX spectrometer [5, 6], considering $^{66}\text{Ni}$ ground and first excited state. The two-nucleon transfer cross section has been calculated, using the spectroscopic factors obtained for the first time within microscopic Interacting Boson Model (IBM) for the direct two-neutron transfer, and the microscopic Interacting Boson Fermion Model IBFM for the two-step process. We have calculated the $^{64,66}\text{Ni}$ theoretical spectra using IBM2 [7] (see figure 1), and the $^{65}\text{Ni}$ one using the interacting boson-fermion model (IBFM) [7] (see figure 1).
Figure 1. Theoretical spectra of the $^{64,66}\text{Ni}$ calculated with IBM-2 scheme, and the $^{65}\text{Ni}$ one with IBFM. Figure taken from Ref. [13], APS Copyright.

Figure 2. Differential cross section of the $^{64}\text{Ni} (^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$ reaction. Figure taken from Ref. [13], APS copyright.

3. The two-nucleon transfer operator in microscopic IBM-2

The calculation of the spectroscopic amplitudes for the two-nucleon transfer reactions in the IBM-2 scheme requires the two-body matrix elements in the Generalized Seniority Scheme (GSS). The matrix elements between fermionic states in the collective subspace are identical to the matrix elements in the bosonic space. Taking into account of the Otsuka- Arima -Iachello (OAI) expansion next to leading order (NLO) [8], we can obtain the two-nucleon transfer operator [9, 10]. The advantage of this operator is that the effects of the pairing interaction are in terms of the occupation of different single-particle orbitals and the two body matrix elements take into account the non-degenerate orbits of the GS states [11]. The calculation of the spectroscopic amplitudes for single nucleon transfer reactions has been performed in the IBFM scheme[12].
The coupled channel Born approximation (CCBA) has been used for the sequential two neutron transfer, whereas the Coupled Reaction Channel (CRC) has been used for the direct two neutron transfer. In figure 2 one can see our results compared with the experimental data.

In the $^{64}$Ni ($^{18}$O,$^{16}$O)$^{66}$Ni two neutron transfer between ground states, both two reaction mechanisms are important, while for the two-neutron transfer to the $^{66}$Ni first excited state, the two-step processes are dominant (See figure 2). These results indicate that the pairing correlation effects are present in the two-neutron transfer to the ground state. It is interesting to observe that for the same nucleus different states prefer different transfer mechanisms.

This formalism for two nucleon transfer reactions [9, 10, 13] developed within the microscopic IBM-2 [14] is particularly appealing, in fact, microscopic IBM-2 allows one to calculate in a realistic way the transition matrix elements for heavy, medium nuclei and it has been exploited for the evaluation of $0\nu\beta\beta$ decay NMEs too [15]. We have just applied this formalism also to two nucleon transfer reaction that are competing processes in respect to DCE in nuclei of $0\nu\beta\beta$ type. It is interesting to observe that the two nucleon transfer is far from saturating the total detected experimental cross section for the DCE, thus pointing to a dominant role of the meson exchange double charge exchange contribution. Indeed, the calculated two nucleon transfer cross section is of the order of $10^{-4} – 10^{-3}$ nb, to be compared with the preliminary extracted experimental cross section of the order of few nb [4].

\[
\frac{d\sigma}{d\Omega} = \frac{k' \mu}{k 2\pi h^2 (2J_P + 1)(2J_T + 1)} \sum_m |M_{if}(m)|^2
\]

where $k$, $k'$ are the initial, final relative momenta of the projectile in the center of mass frame; $\mu$ is the reduced mass of the projectile plus target system; $J_{P/T}$ are the total angular momentum of the initial projectile/target nuclei; and $m = (m_T, m'_T, m_P, m'_P)$ is the set of angular-momentum components.

Figure 3. Preliminary $^{40}$Ca($^{18}$O,$^{18}$Ne)$^{40}$Ar$_{G,S}$. DCE differential cross section in arbitrary units (a.u.).

4. Heavy-ion double charge exchange

A Double Charge Exchange (DCE) reaction is a process induced by a projectile (heavy ion) on a target, in which two protons (neutrons) of the target are converted in two neutrons (protons), being the mass number $A$ unchanged, with opposite transition simultaneously occurring in the projectile. We study the DCE differential cross section of $^{40}$Ca($^{18}$O,$^{18}$Ne)$^{40}$Ar$_{G,S}$ reaction measured by the LNS-INFN by the NUMEN collaboration [16]. The theoretical differential cross section can be obtained by an average of the initial spins and sum over final spins.
quantum numbers of the target and projectile wavefunction. $M_{if}(m)$ is the transition matrix of the DCE process. In DWBA, $M_{if}(m)$ is given by

$$M_{ij} = \langle \Psi_k^- \Phi_f | V | \Psi_k^+ \Phi_i \rangle$$

(2)

where $\Psi_k^\pm$ are the distorted wavefunctions of the nuclei in the center of mass, and $\Phi_{i,f}(r)$ are the intrinsic wavefunctions of the nuclei before and after the interaction. The interaction potential responsible for the DCE between the nuclei is given by $V$, that can be generated from nucleon-nucleon interaction [17]. Here we present a preliminary calculation of DCE $^{40}$Ca($^{18}$O,$^{18}$Ne)$^{40}$Ar$_{G,S}$ differential cross section as shown in figure 3.

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