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Heavy Ion Charge Exchange Reactions as Probes for Beta-Decay

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Abstract. Peripheral heavy ion single and double charge reactions are described by fully quantum mechanical distorted wave methods. A special class of nuclear double charge exchange (DCE) reactions proceeding as a one-step reaction through a two-body process are shown to proceed by nuclear matrix elements of a diagrammatic structure as found also in $0\nu2\beta$ decay. These hadronic Majorana-type DCE reactions (MDCE) have to be distinguished from second order DCE reactions, given by double single charge exchange (DSCE) processes, resembling $2\nu2\beta$ decay. The theoretical concepts of MDCE are discussed. First results show that ion-ion DCE reactions are the ideal testing grounds for investigations of rare second order nuclear processes, giving insight into nuclear in-medium two-body correlation.

1 Introduction

There is broad consensus that $0\nu2\beta$ decay will be a highly promising gateway to physics beyond the standard model of elementary particle physics. Once observed, it will give direct evidence on the Majorana-nature of neutrinos with far reaching implications for neutrino masses, neutrino-matter interactions and flavour mixing up to the question of the matter-antimatter asymmetry in the universe [1–5]. Such a signal has to be distinguished from the two-neutrino beta-decay ($2\nu2\beta$) [6, 7] which is allowed in the standard model. A few nuclei are known to decay by this already rather rare process, as discussed e.g. in Ref. [8]. While the matrix elements are accessible by the observed $2\nu2\beta$ transitions such a check against data does not yet exist for $0\nu2\beta$ processes. Thus, estimates of life times and transition probabilities are relying on theoretical investigations, notoriously showing an uncomfortably large spread of values. Independent tests of the nuclear structure input under controllable dynamical conditions are highly necessary, allowing to evaluate and gauge the theoretical results by an independent process. The field will profit tremendously if a surrogate process could be identified which is technically and physically easily accessible. While single charge exchange (SCE) reactions with light and heavy ions have been studied intensively, see e.g. [9, 10], close to nothing is known about double charge exchange reactions. Only very recently, the NUMEN project has been initiated [11], using heavy ion reactions to explore that unknown territory, also aiming at establishing the relation to double beta decay. Clearly, to establish that connection requires additional efforts in our theoretical understanding of nuclear multi-step reactions. Hence, in section 2 we start with a brief introduction into the theoretical background for single and double single charge exchange reactions. In section 3 the physical concept of Majorana DCE reactions is briefly introduced. First results are discussed in section 4 and in section 5 an outlook will be given.

2 Single Charge Exchange and Double Single Charge Exchange Reactions

Single charge exchange reactions (SCE) have become a widely used tool for studying the spin-isospin response of nuclei. The discovery of the giant Gamow-Teller resonance (GTR) by the pioneering experiments at IUCF [12] initiated widespread experimental and theoretical research activities, continuing with even increasing intensity until today. Over the years, a wealth of data has been accumulated and was used to derive the charge exchange response of nuclei. Comprehensive reviews of the experimental and theoretical methods and achieved results are found in [9] for light ion reactions and in [10] for heavy ion-induced reactions. Peripheral heavy ion collisions, corresponding to direct reactions, are as useful for spectral studies as light ion scattering. An especially appealing aspects is the broad range of projectile-target combinations which, for example, allow to project out selectively specific features, e.g. spin flip and non-spin flip transitions.

As discussed in detail in Ref. [13], the SCE reaction amplitudes are expressed as DWBA matrix elements of the nucleon-nucleon T-matrix with spin-isospin elements of tensorial rank 0 and form factors $V^{(C)}_{ST}$, and rank 2 with corresponding form factors $V^{(Tn)}_{ST}$. They are connecting the initial channel $\alpha = a + A$ and the final channel $\beta = b + B$. The SCE reaction kernel is given by products of nuclear

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form factors

$$K^{(ST)}_{\alpha\beta}(\mathbf{p}) = (4\pi)^2 (V^{(C)}_{ST}(p^2) F^{(ab)\dagger}_{ST}(\mathbf{p}) \cdot F^{(AB)}_{ST}(\mathbf{p}) + \delta_{S1} \sqrt{\frac{24\pi}{5}} V^{(Tn)}_{ST}(p^2) Y^*_2(\hat{\mathbf{p}}) \cdot \left[F^{(ab)\dagger}_{ST}(\mathbf{p}) \otimes F^{(AB)}_{ST}(\mathbf{p})\right]_2) \quad (1)$$

where the rank-2 tensorial coupling relates to the spin degrees of freedom only. Through the form factors $F^{(ab),(AB)}_{ST}$, the kernels contain the spectroscopic information on the nuclear transitions, and the dynamics by the interaction form factors $V^{(C),(Tn)}_{ST}$. In the central interaction part, the scalar product indicates the contraction of the projectile and target form factor with respect to the spin and isospin degrees of freedom. The isospin degrees of freedom are of course projected by the nuclear transitions to the proper combination of $\tau_\pm$ operators. The one-step SCE reaction amplitude is obtained as

$$M_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \int d^3p N_{\alpha\beta}(\mathbf{p}) \mathcal{U}_{\alpha\beta}(\mathbf{p}). \quad (2)$$

where the transition potential is defined by summation over the reaction kernels, Eq.(1). Initial and final state interactions are contained in the distortion coefficient [13, 14]

$$N_{\alpha\beta}(\mathbf{p}) = \frac{1}{(2\pi)^3} \langle \chi^{(-)}_\beta | e^{-i\mathbf{p}\cdot\mathbf{r}} | \chi^{(+)}_\alpha \rangle. \quad (3)$$

The distortion coefficient $N_{\alpha\beta}$ is closely related to the elastic scattering amplitude: For $p \to 0$ and $k_\beta \to k_\alpha$ the definition of the elastic S-matrix is recovered. Thus, in leading order, the above equation corresponds to the folding of the nuclear transition form factors with the ion-ion elastic scattering amplitude. Because of the strong absorption, the distortion coefficient acts mainly as a scaling factor, typically reducing the forward cross section by several orders of magnitudes compared to the plane wave limit. Only at momentum transfers exceeding 100 MeV/c $N_{\alpha\beta}$ leads to modifications of the momentum structure of cross sections.

If we consider, on the other hand, the effective operator underlying the conventional double-SCE two-step reaction mechanism, we find

$$V^{(DSCE)}(\mathbf{13}, \mathbf{24}) \sim \sum_{cC} T_{NN}(\mathbf{3}, \mathbf{4}) \mathcal{G}_{cC}(\mathbf{2} - \mathbf{4}, \mathbf{1} - \mathbf{3}) T_{NN}(\mathbf{2}, \mathbf{1}) \quad (4)$$

where T_{NN} is the isovector nucleon-nucleon T-matrix and $\mathcal{G}_{cC}$ denotes the (full many-body) propagator of the intermediate nuclei reached in the first SCE reaction step. The DSCE reaction amplitude is given effectively by a second order distorted wave expression

$$M^{(DSCE)} = \langle \chi^{(-)}_\beta bB | V^{(DSCE)} | aA \chi^{(+)}_\alpha \rangle. \quad (5)$$

3 Majorana Double Charge Exchange Reactions

Second order quantal processes like heavy ion double charge exchange reactions are of genuine reaction theoretical interest. First of all, until now heavy ion DCE reactions have not been studied, neither experimentally nor theoretically. Some attempts were made on (π^+, π^-) reactions but the notoriously bad energy definition of the incoming pion beams is unfavorable for spectroscopic work. Thus, double charge exchange reactions with heavy ions are much better suited for explorations of weakly populated transitions. Here, we consider collisional charge exchange processes given by elementary interactions between target and projectile nucleons. In accordance with explicit calculations, the mean-field driven transfer contributions are neglected because they are at least of 4th order for DCE reactions considered here [15]. Thus, only processes with changes of the charge partitions but leaving the projectile-target mass partition unaltered will be discussed.

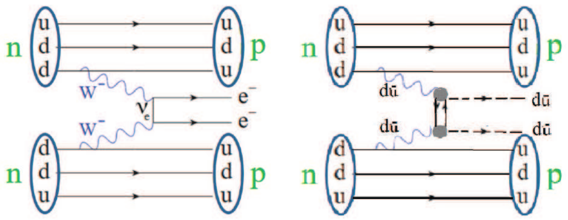

Figure 1. The elementary weak interaction process mediating nuclear $0\nu2\beta$ decay (left) and a corresponding strong interaction process (right) are depicted schematically. The QCD counterpart is given by the simultaneous emission of two $[d\bar{u}]$ pairs in an isovector-vector, e.g. 1^-, configuration (wavy lines), decaying into a pionic $[d\bar{u}]$ configuration and a charge-neutral $q\bar{q}$ pair.

A central question is whether we can identify on the elementary level a correspondences between strong and weak interaction processes. The answer is yes, as illustrated in Fig. 1. Under nuclear structure aspects, the $0\nu2\beta$ decay of a nucleus is nothing but special class of two-body correlation, sustained by the exchange of a (pair of) Majorana neutrino(s) between two nucleons where the interaction vertices are given by the emission of virtual $W^\pm$ gauge bosons. The strong interaction counterpart is a two-nucleon correlation built up by the exchange of a virtual charge-neutral quark-antiquark $(q\bar{q})$ pair accompanied by the emission of a charged $q\bar{q}$ component, thus changing at the same time the nucleonic charges. Similar to the weak process, the strong vertices are originating from gauge bosons, here given by the initial emission of gluons which materialize into two $q\bar{q}$ pairs. At the end, the highly off-shell $q\bar{q}$ compounds will decay into mesons, preferentially into pions but also multi-pion configurations like the scalar and vector mesons.

Both processes become of interest if they reveal their existence and nature in observable signals. In this respect, we encounter a fundamental difference between $0\nu2\beta$ decay and the hadronic process: Only the former may occur in an isolated nucleus while the latter one is inhibited by energy conservation. Thus, in order to observe the double-meson emission by a nucleon pair a partner nucleus is required which takes care of the virtuality of the process by absorbing the two charged virtual mesons. For that pur-

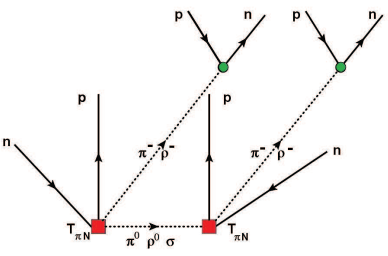

Figure 2. Generic diagram illustrating the hadronic surrogate process for $0\nu2\beta$ decay. A virtual $nn \to pp\pi^-\pi^-$ scattering process, causing the $\Delta Z = +2$ target transition $A \to B$, is accompanied by $nnp^{-1}p^{-1}$ double-CC excitation in the projectile. Crossed diagrams are not displayed.

pose, heavy ion double charge exchange reactions are the ideal tool. The diagrammatic structure of such a reaction is indicated in Fig. 2. The target undergoes a correlated double-meson pair decay $nn \to pp\pi^-\pi^-$ (in fact a $2p2n^{-1}$ 2p-2h transition with coherent emission of a pion pair) and the projectile absorbs the pions by the simultaneous excitation of two np^{-1} -type configurations. Other mesons will contribute as well.

The whole reaction will proceed as a one-step reaction via a special kind of two-body interaction generated by the correlation diagram. Denoting the (in-medium) pion-nucleon T-matrix by $T_{\pi N,\pi' N'}$, the target-part of the interaction is in a somewhat symbolic notation

$$V^{(MDCE)}(\mathbf{13},\mathbf{24}) \sim T_{\pi^- p,\pi^0 n}(\mathbf{1},\mathbf{3}) D_{\pi^0}(\mathbf{1}-\mathbf{2}) T_{\pi^0 n,\pi^- p}(\mathbf{2},\mathbf{4}) \tag{6}$$

where the $n \to p$ target transitions are denoted by **1** and **2**, respectively. The coordinates **3** and **4** indicate the outgoing charged pions, inducing the complementary transitions in the projectile. The correlation built up by the neutral pion is described by the propagator D_{π^0}. A decomposition into irreducible tensors gives rise in particular to an effective rank-2 iso-tensor projectile-target interaction of operator structure $[\boldsymbol{\tau}_{1A} \otimes \boldsymbol{\tau}_{2A}]_2 \cdot [\boldsymbol{\tau}_{3a} \otimes \boldsymbol{\tau}_{4a}]_2$. We recognize immediately the similarity to the nuclear matrix element of $0\nu2\beta$ decay, justifying the name Majorana-DCE. At present, the strengths of the nucleon-nucleon and the pion-nucleon T-matrices are taken from data. More refined description will be scrutinized in future work by an effective field theoretical description and by referring to the data base available for free space $nn \to pp\pi^-\pi^-$ reactions. Previously, the charge-conjugated reaction $pp \to nn\pi^+\pi^+$ reaction and other double-pion production channels were investigated at CELSIUS and COSY [16–20] and more recent also at HADES [21]. Theoretical studies of the on-shell reaction combining meson exchange and resonance excitation are found in [22, 23].

4 Heavy Ion DCE Reactions and Data

The full DCE reaction amplitude is given by the coherent sum of the MDCE and the DSCE amplitudes:

$$\begin{aligned} M_{\alpha\beta} &\sim \langle \chi_\beta^{(-)\dagger}, bB | V^{(MDCE)} + V^{(DSCE)} | aA, \chi_\alpha^{(+)} \rangle \\ &= M_{\alpha\beta}^{(MDCE)} + M_{\alpha\beta}^{(DSCE)} \end{aligned} \tag{7}$$

The results discussed below were obtained fully quantum mechanically by one-step DWBA calculations for the MDCE amplitudes and second order DWBA calculations for the DSCE amplitudes, respectively. Thus, ion-ion interactions are treated to all orders. As discussed in Ref. [13] the strong absorption in grazing ion-ion collisions allows to evaluate the distortion coefficient in black disk approximation. As mentioned before, under such conditions the ISI/FSI effects are resulting effectively in a scaling factor, allowing to relate at forward angles the cross sections to the corresponding plane wave cross sections. Thus, in principle spectroscopic information can be extracted from the data, provided the elastic interactions are known to the necessary precision. In the present calculations, double folding potentials have been used.

First results for a DCE reaction along the line discussed above were measured recently by the NUMEN collaboration [24] for the reaction $^{18}O + {}^{40}Ca \to {}^{18}Ne + {}^{40}Ar$ at $T_{lab} = 15$ AMeV. The reaction leads from the 0^+ ground states of the initial to the 0^+ ground states of the final nuclei, constraining the total angular momentum transfer to $J^P = 0^+$. Second-order DWBA calculations with QRPA transition strengths have been performed along the line of Ref. [13]. For these exploratory investigations only the pionic contributions were included. This leaves open an overall scaling factor which was fixed by normalizing the MDCE cross section to the data point at the smallest scattering angle. The forward peak of the angular distribution is dominated, in fact, by the ($L = 0$, $S = 1$) MDCE component, but the ($L = 2$, $S = 2$) components are of comparable size at larger scattering angles. Moreover, they are essential for the description of the data. Overall, the shape of the measured angular distribution is described decently well in view of the exploratory character of the calculations. In Fig. 3, DSCE and MDCE cross sections are displayed and compared to data as a function of the momentum transfer. Remarkably, the measured angular range ($\theta \lesssim 12^\circ$) covers a momentum range of more than 400 MeV/c. The DSCE cross section was normalized to the large angle region because higher order reactions typically prevail at larger momentum transfers. That conjecture is confirmed by the DSCE angular distribution: Aside from the typical L=0 forward structure the main body of the angular distribution oscillates around a mean-value of a few times $10^{-4} mb/sr$. Cross sections of higher multipolarities are carrying less strengths and are of flatter shape. With all caution, we may conclude that the data are in favor of the one-step MDCE angular distribution. Even if the DSCE cross section would be scaled to the measured forward angle cross section, its shape would not match the observed angular distribution, an observation giving further evidence to the dominance of the MDCE one-step reaction mechanism.

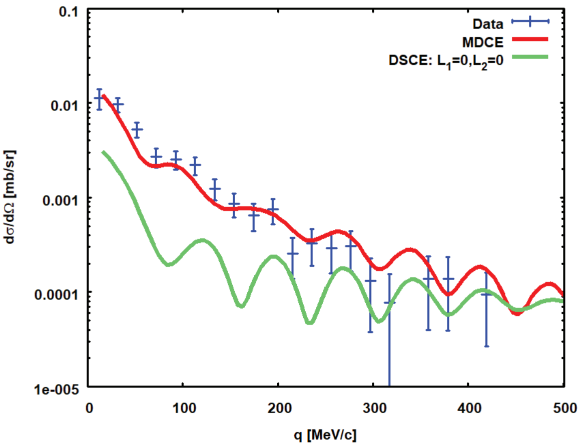

Figure 3. Angular distribution of the DCE reaction $^{18}O+^{40}Ca \rightarrow ^{18}Ne+^{40}Ar$ at T_{lab} = 270 MeV. The one-step MDCE and the two-step DSCE cross sections are shown separately in comparison to the data of Ref. [24].

5 Outlook

A new theoretical scenario for heavy ion double charge exchange reactions was introduced. At the diagrammatic level, structures similar to $0\nu2\beta$ matrix elements have been identified. The hadronic Majorana-DCE process is accessible only by reactions of composite nuclei. We have discussed explicitly the case of a DCE reaction with medium mass ions at relatively low incident energy. ISI and FSI ion-ion interactions were taken into account and the quantum mechanical coherence of the MDCE and the DSCE reaction mechanism was treated properly. The strongly forward peaked measured angular distributions indicate a direct mechanism which indeed is confirmed by the calculations. These first results are very promising by indicating a new way of accessing second order nuclear matrix elements of charge changing interactions. Together with the much better studied SCE reactions and their established usefulness for spectroscopic work, heavy ion DCE reactions are opening a new window to high-precision spectroscopy. Although it will not be possible to insert the extracted matrix elements directly into a $0\nu2\beta$ analysis, DCE reactions provide an unique way to validate nuclear structure models under controllable laboratory conditions by comparison to data on processes of comparable physical content. New impact on theoretical investigations in both reaction and nuclear structure theory is demanded for a quantitative understanding of these special reactions. Although the present calculations do not yet include the full spectrum of contributions, they are establishing the hadronic Majorana-DCE reaction mechanism. The refinements may lead to changes in detail but will not alter the overall picture. An exciting and encouraging result is that the MDCE process is clearly visible, even dominating the cross section at extreme forward angles.

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