Probing Double Beta-Decay by Heavy Ion Charge Exchange Reactions

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Abstract. A special class of nuclear double charge exchange (DCE) reactions proceeding as a one-step reaction through a two-body process are shown to involve nuclear matrix elements of the same diagrammatic structure as 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 second order nuclear matrix elements.

1. Introduction

There is a broad consensus that neutrino-less nuclear double beta-decay will be a highly promising gateway to physics beyond the standard model. However, $0\nu2\beta$ double-beta decay is still a hypothetic process awaiting experimental confirmation. If detected, those decays would 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, 2, 3, 4, 5]. Such a signal has to be distinguished from the two-neutrino $2\nu2\beta$ beta-decay [6, 7] which is fully compatible with the standard model. Although both decays correspond to second order nuclear processes, they are dynamically distinct. Double beta-decay with neutrino emission is a sequential decay process where the leptons are emitted subsequently in an uncorrelated manner. A few nuclei are known to decay by this already rather rare process, as discussed e.g. in Ref. [8, 9]. 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 as discussed in this volume e.g. by Iachello [10]. 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. Hence, the field will profit tremendously if a surrogate process could be identified which is technically and physically easily accessible. While SCE reactions with light and heavy ions have been studied intensively, including our own work [11, 12, 13, 14], close to nothing is known about double charge exchange reactions. Only very recently, the NUMEN project has been initiated [15], using heavy ion reactions to explore that unknown territory, also aiming at establishing the relation to double beta decay. In section 2 the physical concept of
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.

Majorana DCE reactions is briefly introduced. First results are discussed in section 3 and in section 4 an outlook will be given.

2. 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 $(\pi^+, \pi^-)$ reactions but their notoriously bad energy definition of the incoming 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. Thus, only processes with changes of the charge partitions but leaving the projectile-target mass partition unaltered will be discussed.

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.

Such interaction process may occur frequently in nuclei, both on the weak as well as on the strong interaction scale. They remain unobserved if the emitted electrons or charged mesons are reabsorbed by the same nucleon. This will lead to vertex and propagator correction and, as such, contributes to the nucleon in-medium mass operator of a, however, negligibly small strength.
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. As indicated, other isovector mesons as e.g. the rho-meson isotriplet will contribute, too. Contributions of crossed diagrams are not displayed.

Nevertheless, it is worthwhile to keep in mind that we are dealing here with phenomena belonging to the large class of nuclear ground state correlations beyond the commonly studied mean-field sector [16, 17, 18, 19]. Short-range correlations are known to modify nuclear momentum contributions on the level of up to 20%.

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 forbidden 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 purpose, heavy ion double charge exchange reactions are the ideal tool. Diagrammatically, the microscopic dynamics of such a reaction are indicated in Fig. 2. The target undergoes a correlated double-meson pair decay $nn \to pp+\pi^-\pi^-$ (in fact a $2p^{-1}2n$ two particle-two hole transition) and the projectile absorbs the pions by the simultaneous excitation of two $np^{-1}$-type configurations. Other meson configurations 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

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

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 $D_{\pi^0}$. A decomposition into irreducible tensors gives rise in particular to an effective rank-2 iso-tensor projectile-target interaction of operator structure $[\mathbf{\tau}_{1A} \otimes \mathbf{\tau}_{2A}]_2 \cdot [\mathbf{\tau}_{3a} \otimes \mathbf{\tau}_{4a}]_2$. We recognize immediately the
Figure 3. Angular distribution of the DCE reaction $^{18}O + ^{40}Ca \rightarrow ^{18}Ne + ^{40}Ar$ at $T_{\text{lab}} = 270$ MeV. Theoretical results are compared to the data of Ref. [29]. The theoretical cross section includes MDCE and DSCE contributions, added up coherently.

similarity to the nuclear matrix element of $0\nu\beta\beta$ 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 [20] and by referring to the data base available for free space $nn \rightarrow pp\pi^-\pi^-$ reactions. Previously, the charge-conjugated reaction $pp \rightarrow nn\pi^+\pi^+$ reaction and other double-pion production channels were investigated at CELSIUS and COSY [21, 22, 23, 24, 25] and more recent also at HADES [26]. Theoretical studies of the on-shell reaction combining meson exchange and resonance excitation have been performed by the Valencia group [27] and in somewhat extended form by Xu Cao et al. [28].

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

$$V^{(\text{DSCE})}(13, 24) \sim \sum_{cC} T_{NN}(3,4)G_{aC}(2-4,1-3)T_{NN}(2,1)$$

(2)

where $T_{NN}$ is the isovector nucleon-nucleon T-matrix and $G_{aB}$ denotes the (full many-body) propagator of the intermediate nuclei reached in the first SCE reaction step. The differences are obvious, visible in particular in the different operator structures.

3. Heavy Ion DCE Reactions and Data

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

$$M_{\alpha\beta} \sim \langle \chi^{(-)}_{\beta}, bB | V^{(MDCE)} + V^{(DSCE)} | aA, \chi^{(+)}_{\alpha} \rangle = M_{\alpha\beta}^{(MDCE)} + M_{\alpha\beta}^{(DSCE)}$$

(3)

A caveat of heavy ion scattering is the strong role played by initial (ISI) and final (FSI) state ion-ion interactions. The are typically well described by optical potentials. Above, those effects are taken care off by the distorted waves $\chi^{(\pm)}_{\alpha\beta}$. As discussed elsewhere [30, 31] a momentum
space representation allows to separate the ISI/FSI contributions and the nuclear transition form factors,

\[ M_{\alpha\beta} \sim \int d^3 p N_{\alpha\beta}(p)M_{\alpha\beta}(k_a - k_b - p) \quad ; \quad N_{\alpha\beta}(p) = \frac{1}{(2\pi)^3} \langle \chi_{\alpha}^{(-)} | e^{ip\cdot r} | \chi_{\beta}^{(+)} \rangle. \] (4)

The distortion coefficient \( N_{\alpha\beta} \) acts in the strong absorption limit mainly as a scaling factor, typically reducing the forward cross section by several orders of magnitude compared to the plane wave limit. In the calculations discussed below, ion-ion interactions are treated in the strong absorption black disk limit.

First results of a DCE calculation along the line discussed above are shown on Fig. 3 and compared to recent NUMEN data [29] for the reaction \( ^{18}O + ^{40}Ca \rightarrow ^{18}Ne + ^{40}Ar \) at \( T_{lab} = 15 \text{ AMeV} \). The transition strengths are taken from QRPA calculations. The transition potentials were approximated by Gaussians. Only the pionic contributions were included. The forward peak of the angular distribution is dominated, in fact, by the MDCE component. Overall, the data are described decently well in view of the exploratory character of the calculations.

The MDCE and, to a slightly lesser degree also the DSCE process, support large momentum transfers, as it is expected also for the \( 0\nu2\beta \) -decay. This is illustrated in Fig. 4 where the partial MDCE and DSCE cross sections are shown separately. By comparison to Fig. 3 it is seen that the coherent sum of both amplitudes is leading to a complex interference pattern, especially at large momentum transfers. From Fig. 4 is evident that for the \( ^{18}O + ^{40}Ca \) system the MDCE process dominates at small scattering angels, at least for the considered case of purely pionic Majorana-correlations.

4. 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. The lightest possible system is the reaction $^3H + ^3He \rightarrow ^3p + ^3n$. Here, 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.

References

[1] Haxton W C and Stephenson G J 1984 Prog. Part. Nucl. Phys. 12 409
[2] Tomoda T 1991 Rept. Prog. Phys. 54 53
[3] Suhonen J and Civitarese O 1998 Phys. Rept. 300 123
[4] Vergados J D, Ejiri H and Simkovic F 2012 Rep. Prog. Phys. 75 106301
[5] Cremonesi O and Pavan M 2014 Adv High Energy Phys. 951432 (Preprint arXiv:1310.4692 [physics.ins-det])
[6] Goeppert M 1935 Phys. Rev. 48 512
[7] Stefanik D, Simkovic F and Faessler A 2015 Phys. Rev. C 91 064311 (Preprint arXiv:1506.00835 [nucl-th])
[8] Grewe E W and Frekers D 2006 Prog. Part. Nucl. Phys. 57 260
[9] Barabash A S 2015 Nucl. Phys. A 935 52 (Preprint arXiv:1501.05133 [nucl-ex])
[10] Iachello F 2018 see this volume.
[11] Lenske H, Wolter H H and Bohlen H G 1989 Phys. Rev. Lett. 62 1457
[12] Brendel C, von Neumann-Cosel P, Richter A, Schrieder G, Lenske H, Wolter H H, Carter J and Schll D 1988 Nucl. Phys. A 477 162
[13] Bohlen H G, Lenske H et al. 1988 Nucl. Phys. A 488 89
[14] Lenske H and Schrieder G 1998 Eur. Phys. J. A 2 41
[15] Cappuzzello F et al. 2018 Eur. Phys. J. A 54 72
[16] Froemel F, Lenske H and Mosel U 2003 Nucl. Phys. A 723 544 (Preprint [nucl-th/0301038])
[17] Konrad P and Lenske H 2007 Eur. Phys. J. A 33 291 (Preprint [nucl-th/0612078])
[18] Rocco N, Lovato A and Benhar O 2016 Phys. Rev. Lett. 116 192501 (Preprint arXiv:1512.07426 [nucl-th])
[19] Benhar O 2016 Nucl. Phys. News 26 15
[20] Lenske H and Santopinto E work in progress
[21] Johanson J et al. 2002 Nucl. Phys. A 712 75
[22] Clement H et al. 2005 Int. J. Mod. Phys. A 20 1747
[23] El-Bary S A et al. 2008 Eur. Phys. J. A 37 267
[24] Tsuboyama T, Sai F, Katayama N, Kishida T and Yamamoto S S 2000 Phys. Rev. C 62 034001
[25] Sarantsev V V et al. 2007 Phys. At. Nucl. 70 1885
[26] Agakishiev G et al. 2015 Phys. Lett. B 750 184 (Preprint arXiv:1503.04013 [nucl-ex])
[27] Alvarez-Ruso L, Oset E and Hernandez E 199 Nucl. Phys. A 633 519
[28] Cao X, Zou B S and Xu H S 2010 Phys. Rev. C 81 065201 (Preprint arXiv:1004.0140 [nucl-th])
[29] Cappuzzello F et al. 2015 Eur. Phys. J. A 51 145 (Preprint arXiv:1511.03858 [nucl-ex])
[30] Bellone J et al. 2018 see this volume.
[31] Lenske H, Bellone J, Colonna M and Lay J A 2018 Phys. Rev. C (submitted)