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A short history of double charge exchange research: From early disappointments to modern excitements

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Summary. — Only since about a decade, the large discovery potential of nuclear double charge exchange (DCE) reactions was realized after abolishing the traditional view of being given by the exchange of proton and neutron pairs between projectile and target nuclei. A new field of research on nuclear reaction and nuclear structure physics is emerging, focused on a specific type of higher order nuclear spectroscopy, inaccessible otherwise and of large interest for double beta decay.

1. – Historical disappointments and failures

Soon after the advent of the first generation of heavy ion facilities around 1970 also heavy ion double charge exchange (HIDCE) reactions were studied as early as in the seventies of the last century [1, 2]. The focus was on the production of nuclei far off stability which are of large interest for the nucleosynthesis in stellar processes and, as known today, in mergers of astrophysical compact object like neutrons stars and black holes.

Theoretically, HIDCE reactions were – and still are – a big challenge to nuclear theory. The early theoretical studies tried to explain the DCE process by sequences of proton and neutron pair transfer reactions. However, with the theoretical tools, methods, and computer power available 50 years ago, nuclear theory was confronted with extreme difficulties to model HIDCE reaction dynamics quantitatively. Since there were also large experimental difficulties to measure the small DCE cross sections with sufficient statistical certainty, systematic DCE studies were discouraged.

A complectly independent DCE program was started at the Los Alamos laboratory after the newly founded Los Alamos Meson Physics Facility (LAMPF) came into operation in 1972 with its, at that time, most powerful linear proton accelerator. As discussed also in the recent review articles [1, 2], the DCE research activities at LAMPF were centered around $(\pi^{\pm}, \pi^{\mp})$ reactions on nuclear targets. Pions as isopin $I = 1$ mesons are intrinsically isovector particles and as such should be the prefect probes for isospin studies on nuclei. The LAMPF experiments were trying to establish pionic DCE reactions as unique probes for predicted but still not observed higher order collective modes of nuclear excitations. If successful, the experiments would have giving nuclear structure and reaction physics access to the unexplored territory of in–medium two–body phenomena and more complex correlation dynamics in the strongly interacting dense nuclear environment. Of utmost interest were double giant resonance searches in general and investigations of double excitations of specific isovector modes in particular. The program was motivated not to the least by the large impact on nuclear physics by the (p, n) single charge exchange (SCE) research activities at the Indiana University Cyclotron Facility (IUCF). The aim was to establish pion DCE reactions as a complementary tool for studies of double excitations of isobaric analogue states (DIAS) and Double Gamow–Teller Resonances (DGTR). However, during the decade–long experimental campaign and the accompanying theoretical work, the data and the theory results were disappointing by not showing convincing evidence for the expected DCE modes. Iinally it was decided to the close LAMPF.

The caveat of reaction physics with pions is the comparatively weak interaction at low energies, reflecting to some extent the Goldstone boson character of the pion. Only well above the threshold region the interaction gains strength from the (strongly energy dependent) coupling to elastic pion–nucleon resonances where the widely known $\Delta_{33}(1232)$ resonance is only the lowest member of a large variety of higher lying states. The LAMPF experiments were done mostly at beam energies below the resonance region, thus missing important contributions.

At the time of the pion–DCE activities at LAMPF, new interest arose on HIDCE reactions in the late 1980ies. During the 1980ies heavy ion beams were found to be quite useful for SCE research from excitations of low–lying states to studies of nucleon resonances in nuclei, see, *e.g.*, [1, 3, 4]. Experimental DCE program were newly set up at the heavy ion facility at Michigan state university (MSU) in East Lansing/USA and at the GANIL laboratory in Caen/France. But the beam energies and intensities available at that time did not lead to clear signals either, thus repeating the undecided situation of pion DCE. The conclusion was to abandon HIDCE research under the experimental and theoretical conditions of that time.

2. – The new era of DCE excitements

The principal interest on DCE reaction, however, survived. It took about two decades before new attempts were made in the first decade of the new millennium to reexamine once again the usability of HIDCE reactions. That brave move was motivated and supported by the meanwhile substantial improvements on experimental equipments and methods, making feasible to relaunch DCE reaction studies. Efforts in that direction were made especially in Japan and in Italy and, as far as theory is concerned, also in Germany. In this context, the NUMEN project is outstanding [2, 5] by the unique experimental conditions at LNS Catania and, equally important, by an extraordinary intense worldwide collaboration of experiment and theory groups.

The concepts, interdependencies, and relations of modern DCE physics and the connected neighbouring fields are depicted schematically in fig. 1. The experiments, in preparation or planned for the near future, require equipment going to the limits of the current possibilities regarding not only accelerator and beam technologies but also for data acquisition and handling and software tools for data analyses [2, 6]. The experience with the already performed experiments leads to the conclusion that a multi–methods and a multi–messenger approach is necessary and indispensable for the full understand-

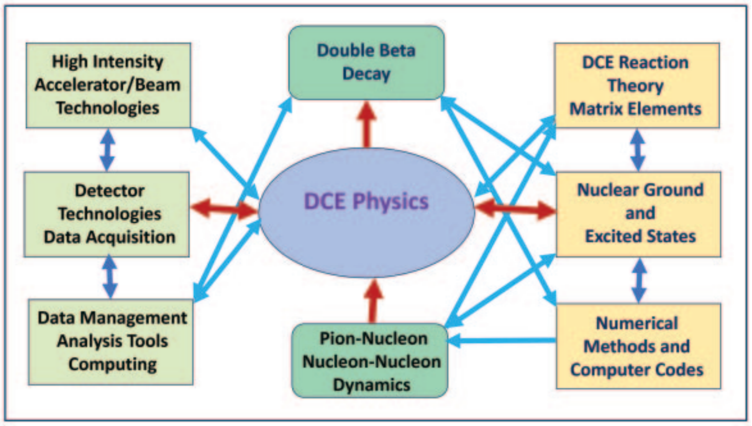

Fig. 1. – The interdependencies and relations of modern DCE physics as a high score technology project (left) and a challenging task for nuclear structure and reaction theory (right) with important connections to DBD physics (top) and input from hadron dynamics (bottom).

ing of second order processes like DCE reactions and spectroscopy. That approach is illustrated in fig. 2 for the complete study of the reaction and nuclear structure network required for the detailed investigation of the ^{76}Ge(^{20}Ne,^{20}O)^{76}Se DCE reaction. That figure emphasizes also the urgent need for theoretical work on developing methods and numerical schemes to treat the problem adequately.

Given that the experimental and theoretical foundations are on safe grounds, modern DCE physics provides the unique opportunity to enlarge the realm of nuclear reaction physics to precise spectroscopy of higher order nuclear processes. Studies of that type have been drawing increasingly large attention in recent years, where γ–spectroscopy is a leading field as found in [7, 8]. Our understanding of processes like DCE reactions, $2\nu2\beta$ and $0\nu2\beta$ decay, and $\gamma\gamma$ emission is in an early, still premature stage, waiting for extensions and completions.

DCE physics is aiming mainly on two topics, both addressing important questions of central interest for strong and weak interaction physics, and with all caution maybe even for the Standard Model. Under nuclear physics aspects, DCE reactions are the perfect tool to study higher order processes in nuclei and their interactions. The present understanding is that these reactions indeed include pair transfer processes as assumed initially, but in many cases their contributions are suppressed because they are mean–field processes depending strongly on favorable matching conditions in quantum numbers and energies. Collisional second order processes as Double Single Charge Exchange (DSCE) driven by sequential nucleon-nucleon interactions and the newly postulated Majorana DCE (MDCE) mechanism, given by a pair of virtual $(\pi^{\pm}, \pi^{\mp})$ pion–nucleon interactions are not hampered by such conditions. They will be the ubiquitous scenarios under which DCE reactions proceed. Clarification and possibly confirmation of these issues on a quantitative level are connected with high demands on innovative new concepts for nuclear matrix elements and reaction amplitudes, connecting nuclear states and reaction channels which differ by two units of isospin. At present. we are at the stages of collecting experience. It is worth remembering that DBD theory has been investigating that problem for decades with stepwise, slow progress as seen by the persistent spread

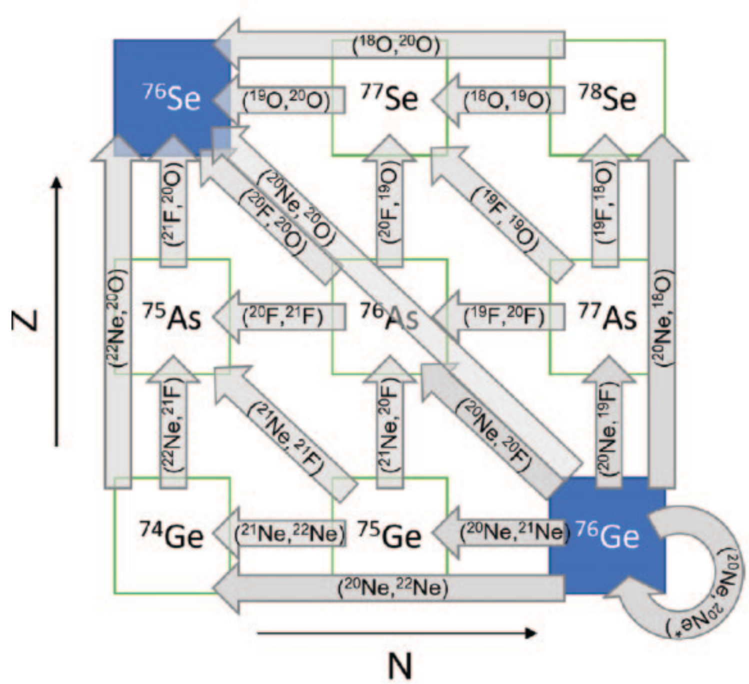

Fig. 2. – The reaction network to be considered in a complete analysis of the ^{76}Ge(^{20}Ne,^{20}O)^{76}Se DCE reaction (from ref. [2]).

of the calculated nuclear matrix elements for $0\nu2\beta$–decay by factors of 2. Once DCE reactions are under control to a level that precise spectroscopic information can be derived from the data and confirmed by theory – and vice versa – nuclear reactions will serve to test independently the nuclear wave functions, albeit not exactly the same matrix elements, entering into DBD and DCE processes.

REFERENCES

[1] Lenske H., Cappuzzello F., Cavallaro M. and Colonna M., *Prog. Part. Nucl. Phys.*, **109** (2019) 103716.
[2] Cappuzzello F. *et al.*, *Prog. Part. Nucl. Phys.*, **128** (2023) 103999.
[3] Lenske H., Wolter H. H., and Bohlen H. G., *Phys. Rev. Lett.*, **62** (1989) 1457.
[4] Brendel C., von Neumann-Cosel P., Richter A., Schrieder G., Lenske. H., Wolter H. H., Carter J., and Schuell D., *Nucl. Phys. A*, **477** (1988) 162.
[5] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **54** (2018) 72.
[6] Calvo Daniela *et al.*, *Nucl. Instrum. Methods A*, **1041** (2022) 167336.
[7] Soederstroem P. A., Capponi L., Aciksoz L., Otsuka T., Tsoneva N., Tsunoda Y., Balabanski D. L., Pietralla N., Guardo G. L., Lattuada D., Lenske H., Matei C., Nichita D., Pappalardo A. and Petruse T., *Nat. Commun.*, **11** (2020) 3242.
[8] Isaak J., Savran D., Pietralla N., Tsoneva N., Zilges A., Eberhardt K., Geppert C., Gorges C., Lenske H, and Renisch D., *Phys. Rev. C*, **108** (2023) L051301.