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A multi–channel study of the ^{20}Ne + ^{130}Te system within the NUMEN project

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Abstract. The NUMEN project aims to measure specific reaction cross sections to provide experimentally driven information about nuclear matrix elements of interest in the context of neutrinoless double beta decay ($0\nu\beta\beta$). In particular, it was proposed to use heavy – ion induced double charge exchange reactions as tools towards the determination of information on the nuclear matrix elements of $0\nu\beta\beta$, strongly motivated by a number of similarities between the two processes. To this extent, the ^{20}Ne + ^{130}Te system was experimentally investigated in a multi-channel approach by measuring the complete net of reactions channels, namely double charge exchange, single charge exchange, elastic and inelastic scattering, one – and two – nucleon transfer reactions, characterized by the same initial projectile and target nuclei. The goal of the study is to fully characterize the properties of the nuclear wavefunctions entering in the $0\nu\beta\beta$ decay nuclear matrix elements. The experimental setup, the data reduction and some of the obtained results for the ^{20}Ne + ^{130}Te system will be presented and discussed.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is one of the "hot" subject in physics research nowadays [1, 2]. The process, forbidden in the Standard Model framework, has not been experimentally observed yet and only experimental lower limits on the $0\nu\beta\beta$ half-time are available for some isotopes [3, 4, 5, 6, 7]. In this extremely rare yet elusive process, a nucleus with mass and atomic numbers (A,Z) is transformed into a new one with mass and atomic numbers (A,Z+2) emitting also two electrons or to (A,Z-2) emitting two positrons. Since no neutrinos or antineutrinos are emitted, the aforementioned processes violate the lepton number conservation law. The decay rate of the $0\nu\beta\beta$ together with a precise determination of its nuclear matrix elements (NMEs) provide a unique tool to access the effective neutrino mass. The measurement of the half-life of $0\nu\beta\beta$ is a challenging aspect but, the uncertainties met in the NMEs determination are also large, approaching a factor of 3-4 introducing an uncertainty of an order of magnitude in the effective neutrino mass [2, 8].

To this extent, the NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project [9, 10] aims to access information on the $0\nu\beta\beta$ NMEs through the study of the heavy-ion (HI) induced double charge exchange (DCE) reactions on all $\beta\beta$ decay candidate targets. This is strongly motivated by a number of similarities between the two processes taking also into account that the NMEs of the two processes appeared to be in linear correlation [11, 12, 13]. A precise determination of the NMEs of the surrogate process required not only the measurement of the DCE reaction but also, all the reactions channels characterized by the same initial projectile and target nuclei. Therefore, NUMEN aims to experimentally investigate the complete net of reaction channels including the:

- Double Charge Exchange reaction (DCE),
- Single Charge Exchange reaction (SCE),
- one-proton transfer reaction,
- one-neutron transfer reaction,
- two-proton transfer reaction,
- two-neutron transfer reaction,
- elastic scattering, and
- inelastic scattering channel.

An illustrative example of the reaction paths for the system discussed in this article is presented in Fig. 1

Several HI systems are currently investigated in this phase of the NUMEN project [10, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. The heaviest of the targets explored so far in NUMEN is the ^{130}Te [18, 21, 28]. CUORE experimental campaign [3] is also searching to measure the $0\nu\beta\beta$ half-life for this nucleus providing so far experimental limit for the $0\nu\beta\beta$ half-life. Another experimental campaign in construction, SNO+ [29], also aims to explore the ^{130}Te as a $0\nu\beta\beta$ candidate. The first experiment related to the study of the ^{20}Ne + ^{130}Te system within the NUMEN and NURE projects [9, 30] will be presented in the present article, providing a first input to a forthcoming exploration of the system in the next phase of the NUMEN project.

2. Experimental details

The relevant experiment was visualized at the MAGNEX facility[31] of the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy where the NUMEN experimental campaign takes place. A $^{20}Ne^{10+}$ beam was accelerated by the K800 Superconducting Cyclotron at 306 MeV (15.3 MeV/nucleon) incident energy and impinged on a $\sim 250\ \mu g/cm^2$ ^{130}Te target evaporated onto a thin carbon foil with a thickness of $\sim 40\ \mu g/cm^2$. Two different post - stripper materials, C_3H_6 and carbon (each one in a different set of runs),

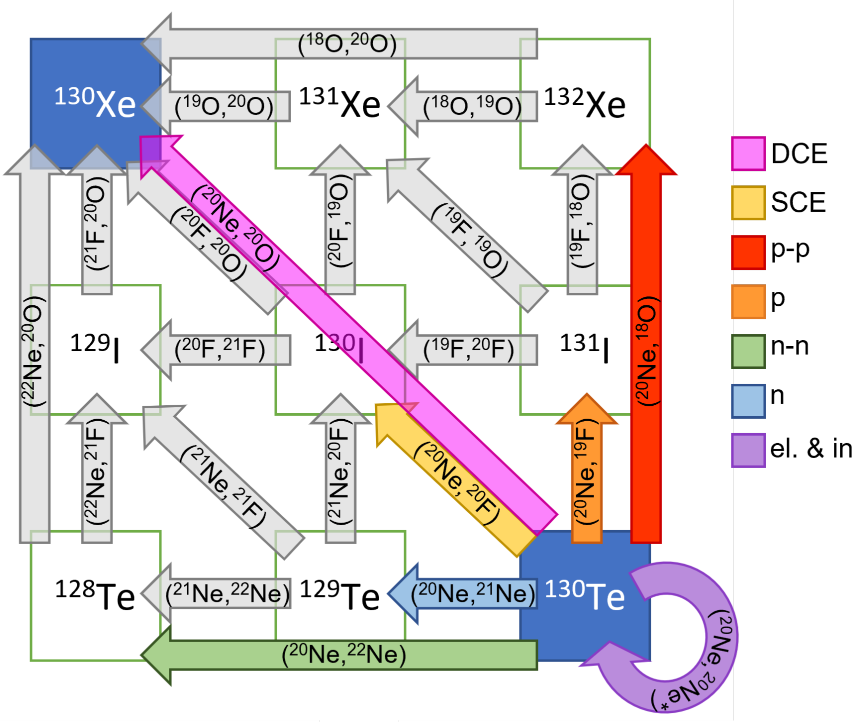

Figure 1. Network of possible nuclear reaction routes connecting initial and final states in the ^{20}Ne+^{130}Te DCE reaction. Colour labels are indicated in the legend.

were located downstream the target position in order to minimize the amount of ^{20}Ne^{8+} and ^{20}Ne^{9+} events [28].

The various ejectiles were momentum analyzed by the MAGNEX magnetic spectrometer while the different ions were detected by the MAGNEX Focal Plane Detector (FPD) [32, 33]. The MAGNEX FPD consists of a gas tracker followed by a wall of 60 single silicon detectors without any intermediate foils but with only an entrance mylar window. The gas tracker includes six sections each one having at the top a proportional wire (DC). A set of 224 induction pads is mounted above each DC wire allowing the measurement of the horizontal position (X_f) and angle (θ_f). The present experiment was the first one on which the new configuration with the six DCs [32] was used. Furthermore, the electron drift time measurements inside the gas allow for the determination of the vertical position (Y_f) and angle (ϕ_f). The energy loss (ΔE_{tot}) of the ions inside the gas is measured by the DCs wires while, the residual energy E_{resid} is measured by the silicon detectors. Finally, the angular and energy coverage of MAGNEX is presented in Table 1 for the measurement of the different reaction channels.

3. Data reduction

The particle identification (PID) was performed as described in Ref. [34]. In particular, the first step of the PID for the reaction channels of our interest is the separation based on the ions atomic number (Z) by means of the standard ΔE–E technique. A typical ΔE–E spectrum is shown in Fig. 2 for a single silicon detector. After selecting the Z of interest, the mass identification is feasible via the X_f–E_{resid} (horizontal position versus residual energy measured by a single silicon detector) spectra through the relation:

$$X_f \propto \frac{\sqrt{m}}{q}\sqrt{E_{resid}}, \tag{1}$$

Table 1. Angular and energy coverage of MAGNEX in the measurement of the different reaction channels. For each reaction channel of interest (first column), the detected ion and the angle(s) of the MAGNEX optical axis are presented in the second and third column, respectively. The covered angular range (fourth column) for a specific E_x range (fifth column) is also presented.

Reaction	Detected ion	θ_{opt} (°)	θ_{lab} (°)	E_x (MeV)	See also
DCE	^{20}O	-3	0 to 9.5	0 to 10	Ref. [21]
			0 to 6	10 to 25	Ref. [21]
SCE	^{20}F	10	7 to 15	0 to 35	
1p-transfer	^{19}F	10	8 to 15	0 to 28	
1n-transfer	^{21}Ne	10	8 to 15	0 to 4	
2p-transfer	^{18}O	-3	0 to 7	0 to 8	
2n-transfer	^{22}Ne	10	8 to 15	0 to 14	
(quasi-)elastic	^{20}Ne	8, 13, 20	3 to 26		Ref. [18]
inelastic	^{20}Ne	13, 20	13 to 23	$\sim$ 1.6	Ref. [18]
			14 to 19	$\sim$ 2.5	Ref. [18]

where m and q are the particle mass and charge state, respectively. In this way, the ions with a different $\frac{\sqrt{m}}{q}$ ratio, appear at different loci at the X_f–E$_{resid}$ representation as it is shown in Figs. 3,4 For all the cases of interest, both atomic number and mass separation is excellent. This is essential particularly for reaction channels with extremely tiny cross section, such as the DCE one.

Having identified the reaction channels of interest, a software high − order (10^{th}) ray reconstruction is applied to the data [35] and, the excitation energy spectra are obtained. Subsequently, the absolute cross sections are deduced for each of the reaction channels of interest.

4. Results and perspectives

The excitation energy spectrum for the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction, shown in Fig. 5 [21], allows for the determination of the DCE cross section for the ^{130}Te$_{g.s.}$ → ^{130}Xe$_{g.s.}$ transition, the best estimate of which is 13 nb (between 3 and 18 nb in a 95% confidence level) in the angular range $0.0° \leq \theta_{lab} \leq 9.5°$ and in the energy range -1 MeV $\leq E_x \leq$ 1 MeV [21]. Except the transition to the ^{20}O$_{g.s.}(0^+)$ + ^{130}Xe$_{g.s.}(0^+)$, a contribution due to the transition to the ^{20}O$_{g.s.}(0^+)$ + ^{130}Xe$_{0.536}(2^+)$ may be expected due to the finite experimental energy resolution which is estimated at $\sim$ 0.5 MeV from similar experiments in MAGNEX facility [19, 20]. It should be underlined the absence of any spurious events in the negative E_x region while, any background due to to target backing and post-stripper material is expected at $E_x > 33$ MeV due to kinematics. The measurement provides, for the first time, an estimation of the tiny DCE cross section for the transition under study. It should be noted that the ^{130}Te is the heaviest of the targets under investigation at the second phase of the NUMEN project and one of the heaviest targets to be investigated in the fourth phase of the project. The latter is launched after the upgrade of the INFN - LNS Superconducting Cyclotron and the MAGNEX FPD, more details of which can be found in Refs. [36, 37, 39, 40].

Except the experimental investigation of the DCE reaction presented in Ref. [21], the data analysis of the quasi-elastic and inelastic scattering channels is already completed and reported in Ref. [18]. The quasi-elastic and inelastic scattering cross-section angular distributions were

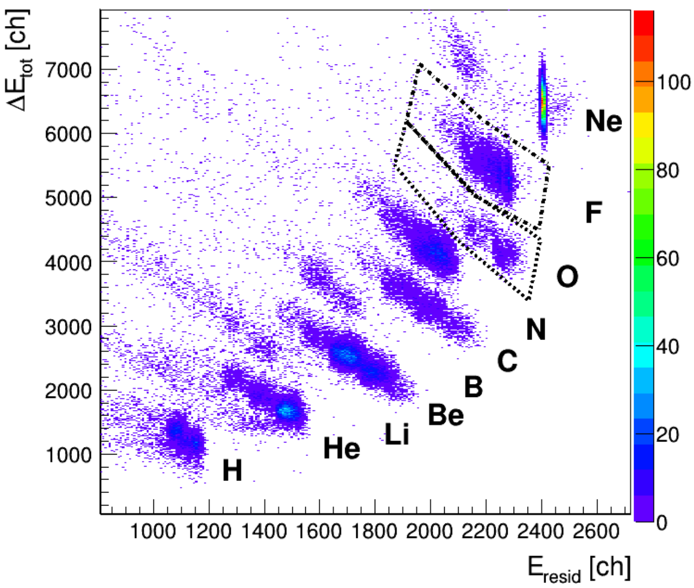

Figure 2. Typical ΔE_{tot} - E_{resid} spectrum for a single silicon detector of the FPD. Graphical selections of oxygen and fluorine ions are depicted with dashed and dot-dashed contour respectively.

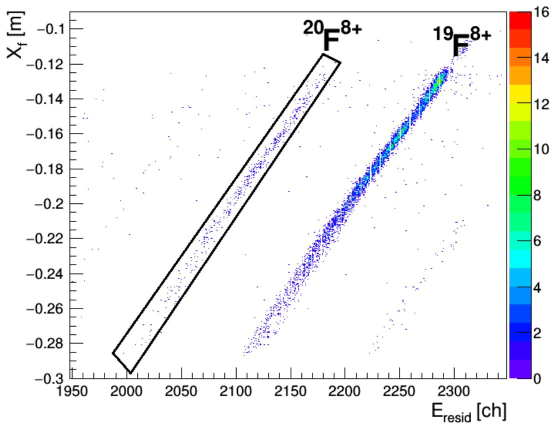

Figure 3. Horizontal position (X_f) versus residual energy (E_{resid}) spectrum after applying the graphical cut on fluorine ions of Fig. 2. The graphical selection of $^{20}F^{8+}$ (SCE) is illustrated with the solid line. See text for more details.

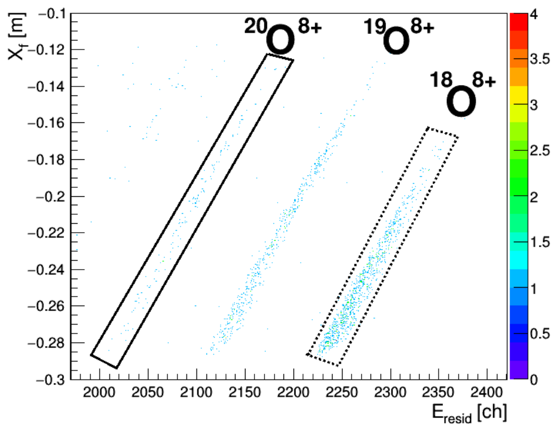

Figure 4. Same as in figure 3 but, after applying the graphical cut on oxygen ions of Fig. 2. The graphical selections of $^{20}O^{8+}$ (DCE) and $^{18}O^{8+}$ (2p-transfer) ions are illustrated with the solid and dashed line respectively.

compared to theoretical calculations within the optical model, one-step distorted wave Born approximation and coupled-channels frameworks, presenting in overall a very good agreement among them [18]. Finally, the data analysis for the rest of the reaction channels, i.e. the SCE,

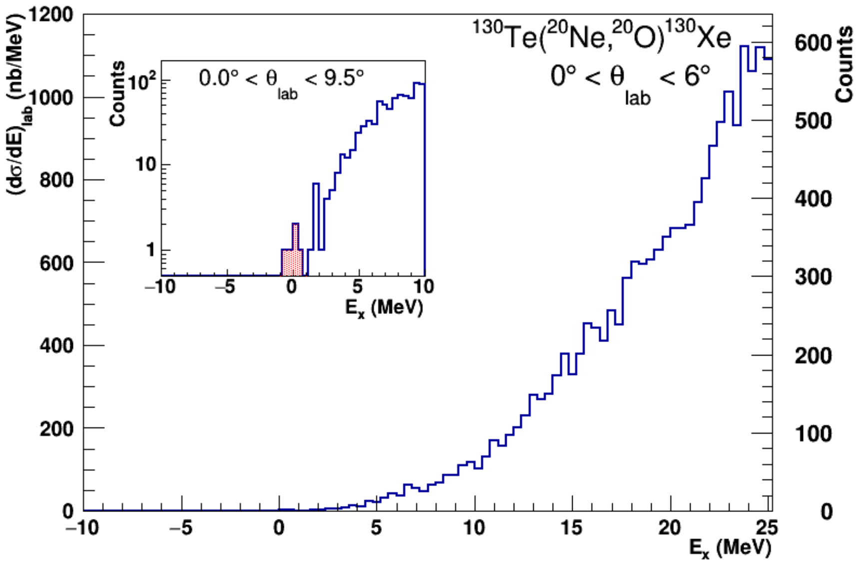

Figure 5. Excitation energy spectrum for the ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction at 306 MeV incident energy and $0.0° \leq \theta_{lab} \leq 6.0°$ angular range. A zoomed view for E$_x$ < 10 MeV and full angular range $0.0° \leq \theta_{lab} \leq 9.5°$ is shown in the inset. The ^{130}Te$_{g.s.} \rightarrow$ ^{130}Xe$_{g.s.}$ region (-1 MeV $\leq E_x \leq$ 1 MeV) is indicated with the red hatched area. Figure from Ref. [21].

one-nucleon and two-nucleon transfer, is in progress.

It should be pointed out that two successive SCE reactions, multi-nucleon transfer processes or a combination among them may -in principle- lead to the production of ^{20}O ejectiles. The measurement of the SCE channel and the single- and two-nucleon transfer reactions may provide the appropriate constraints on the estimated contribution of these competitive processes to the DCE cross section. As regards the multi-nucleon transfer, a recent theoretical work for the ^{20}Ne+^{116}Cd system at the same energy with the present study pointed to a negligible contribution of such process to the overall DCE cross-section [38].

The advent of the upgrade of the LNS facilities will allow for a deeper investigation of the ^{20}Ne + ^{130}Te system at different incident energies while, an investigation of the ^{130}Xe nucleus is also planned (symmetric processes to the ones shown in Fig. 1). Into this context, the development of a gas or implanted ^{130}Xe target is necessary and a relevant research is currently in progress [39, 41, 42, 43].

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