FIRST MEASUREMENT OF THE ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn REACTION AT 15 A MeV*

S. Calabrese[a,b], F. Cappuzzello[a,b], D. Carbone[a], M. Cavallaro[a] C. Agodi[a], L. Acosta[c], D. Bonanno[d], D. Bongiovanni[a] T. Borello-Lewin[e], I. Boztosun[f], D. Calvo[g], E.R. Chàvez Lomeli[c], N. Deshmukh[a], P.N. de Faria[h], P. Finocchiaro[a] M. Fisichella[g], A. Foti[b,d], G. Gallo[b,d], A. Hacisalihoglu[a,i] F. Iazzi[g,j], R. Introzzi[g], G. Lanzalone[a,k], R. Linares[h] F. Longhitano[e], D. Lo Presti[b,d], N. Medina[e], A. Muoio[a] J.R.B. Oliveira[e], A. Pakou[l], L. Pandola[a], F. Pinna[g,l], S. Reito[d] G. Russo[b,d], G. Santagati[a], O. Sgouros[l] S.O. Solakci[f], V. Soukeras[l], G. Souliotis[l], A. Spatafora[a,b] D. Torresi[a], S. Tudisco[a], A. Yildirim[f], V.A.B. Zagatto[h]

for the NUMEN Collaboration

[a]INFN, Laboratori Nazionali del Sud, Catania, Italy
[b]Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy
[c]Instituto de Fisica, Universidad Nacional de Mèxico, Mexico City, Mexico
[d]INFN, Sezione di Catania, Catania, Italy
[e]Departamento de Física Nuclear, Universidade de São Paulo, São Paulo, Brazil
[f]Departament of Physics, Akdeniz Üniversitesi, Antalya, Turkey
[g]INFN, Sezione di Torino, Turin, Italy
[h]Instituto de Física, Universidade Fluminense, Niterói, Rio de Janeiro, Brazil
[i]Institute of Natural Sciences, Karadeniz Teknik Üniversitesi, Trabzon, Turkey
[j]Dipartimento di Scienza Applicata, Politecnico di Torino, Turin, Italy
[k]Facoltà di Ingegneria e Architettura, Università di Enna “Kore”, Enna, Italy
[l]Physics Department, University of Ioannina, Ioannina, Greece

(Received January 9, 2018)

The NUMEN Collaboration proposes an original experimental method to get information on the nuclear matrix elements involved in the neutrinoless double beta decay, exploring its connection with double charge-exchange nuclear reactions using heavy ions. The first results for the data reduction of the ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn experiment at 15 A MeV are presented.

DOI:10.5506/APhysPolB.49.275

* Presented at the XXXV Mazurian Lakes Conference on Physics, Piaski, Poland, September 3–9, 2017.

1. Introduction

Recently many efforts have been directed towards the study of neutrinoless double-beta ($0\nu\beta\beta$) decay. If observed, it would establish the Majorana nature of neutrinos, also offering the possibility to determine the effective neutrino mass. The possibility of observing this process experimentally depends on the values of the parameters entering the expression for the half-life [1]. The Nuclear Matrix Elements (NMEs), in particular, are at the moment evaluated through theoretical calculations only [2–4] with a moderate agreement between the different models. The NUMEN (NUclear Matrix Elements of Neutrinoless Double Beta Decay) project [5, 6] proposes to use nuclear reactions, in particular double charge-exchange (DCE) ones, as a tool to get experimental information on $0\nu\beta\beta$ NMEs. Within it, the absolute cross sections of the DCE transitions and competing multi-nucleon transfer channels for candidate nuclei for $0\nu\beta\beta$ decay will be measured. The project is made possible by the use of the Superconducting Cyclotron beams and MAGNEX magnetic spectrometer [7–9], a high-performance instrument used in a variety of heavy-ion physics studies [10–13]. The physics case and the details of the NUMEN project are discussed in Refs. [5, 14].

DCE reactions are challenging from the experimental side due to their very low cross sections and a large background of competing processes. In addition, high mass, angular, and energy resolutions are needed to isolate specific transitions in such heavy-ion collisions. Moreover, an important requirement is to measure energy spectra and absolute cross-section angular distributions down to zero degrees. In the past, few attempts have been reported for heavy-ion induced DCE reactions. No studies, to our knowledge, concerned the (^{20}Ne,^{20}O) reaction, which is interesting as it promotes $\beta^-\beta^-$-like transitions in the target.

In this paper an experimental measure of a DCE reaction on a ^{116}Cd target through the (^{20}Ne,^{20}O) reaction at $15\,A\,$MeV is presented for the first time. The experimental set-up and the data reduction procedure are discussed.

2. Experimental setup

The experiment was performed at the INFN-LNS laboratory in Catania. A ^{20}Ne^{10+} beam, accelerated by the K800 Superconducting Cyclotron to $15\,A\,$MeV, impinged on a 1360 ± 140 μg/cm^2 thick ^{116}Cd target coupled to a 1000 ± 100 μg/cm^2 thick carbon post-stripper. The latter was included in order to minimize the contribution of the beam due to lower charge states (8^+ and 9^+) generated by the charge redistribution in the target. The ions thus produced, especially the ^{20}Ne^{8+} elastically scattered at forward angles, have a magnetic rigidity close to that of the ejectiles of interest for DCE (^{20}O^{8+})

and other concurrent channels. Consequently, they enter in the focal plane detector (FPD) acceptance, compromising the detector tolerable rate. In order to further reduce these contributions, the spectrometer momentum acceptance was limited to protect the FPD from the high counting rate; for this purpose two aluminium screens were mounted before the entrance of the focal plane to stop the unwanted ions. The beam charge was collected by a Faraday cup located 15 cm downstream of the target. A total charge of 2.9±0.3 mC was measured. The outgoing $^{20}O^{8+}$ ejectiles were momentum analyzed by the MAGNEX spectrometer [7] and detected by its FPD [15]. Moreover, thanks to the large momentum acceptance, also one-proton and two-proton transfer as well as single charge exchange (SCE) reaction products were simultaneously detected using the same magnetic fields. A representation of the measured transitions at the target is shown in Fig. 1.

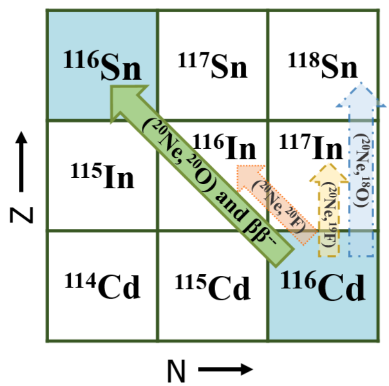

Fig. 1. Reaction channels simultaneously detected using the same magnetic fields: (^{20}Ne,^{20}O) DCE in solid $\nwarrow$; (^{20}Ne,^{20}F) SCE in dotted $\nwarrow$; (^{20}Ne,^{19}F) 1-proton transfer in dashed $\uparrow$; (^{20}Ne,^{18}O) 2-proton transfer in dashed-pointed $\uparrow$.

The MAGNEX FPD is a low-pressure gas detector with five sets of proportional wires to measure the energy loss ΔE of the ions crossing it. Moreover, four sets of 224 induction pads allow measuring the horizontal position $X_{\rm foc}$ and angle $\theta_{\rm foc}$ at the focal plane. Electron drift time measurements give access to the vertical position $Y_{\rm foc}$ and angle $\phi_{\rm foc}$. A wall of 57 silicon pad detectors is placed downstream from the FPD tracker to stop the ions and measure their residual energy $E_{\rm resid}$.

The measurement was performed with the spectrometer optical axis centered at $\theta_{\rm lab} = 8°$. Thanks to the large angular acceptance of MAGNEX, an angular range of $3° < \theta_{\rm lab} < 14°$ in the laboratory frame was covered.

3. Data reduction

The first step of the focal plane data analysis is the calibration of the horizontal X_i and vertical position Y_i measured by FPD, as described in Ref. [16]. The following step is the identification of the $^{20}O^{8+}$ ejectiles, which are first identified in atomic mass number (Z) using the ΔE–E technique. The mass number (A) and the charge state (q) are then deduced using the correlation between the ion trajectory and its kinetic energy in the magnetic field, due to the Lorentz force [17]. This is reflected in an almost quadratic relation between the horizontal position of the ejectiles at the focal plane X_{foc} and their residual energy at the same position, depending proportionally on the ratio $\sqrt{m}/q$. Thanks to this identification technique the mass resolution required to clearly separate the oxygen isotopes has been reached, as shown in Fig. 2.

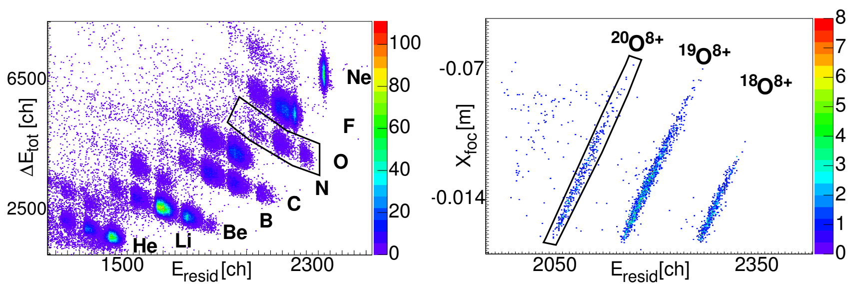

Fig. 2. Example of ion identification plots for the $^{20}O^{8+}$ ions. Left panel: Sum ΔE_{tot} of the energy collected by the proportional wires corrected for the different paths (consequence of different incident angles) *versus* the residual energy E_{resid} measured by a single silicon detector. Right panel: Horizontal position at the focal plane X_{foc} *versus* E_{resid} for oxygen ions selected by the gate plotted in the left panel.

After the particle identification, the positions and the angles measured at the focal plane were used to reconstruct, event by event, the phase space parameters at the collision point. This reconstruction is performed using an algebraic method which calculates the spectrometer transport map (M) up to the 10$^{\text{th}}$ order using the COSY INFINITY code [18]: knowing the magnetic fields and geometry used during the experiment it is possible to determine the trajectory of every ion [19–22]. Simulated data are then compared to the experimental ones in order to test the accuracy of M in reproducing the higher-order aberrations present in the experimental scatter plots. After this, the inverse map (M^{-1}) is generated using COSY INFINITY and applied to the measured data at the FPD, thus returning the initial momentum vector at the target point. The scattering angle in the laboratory frame

$\theta_{\rm lab}$ as well as the excitation energy of the residual nucleus $E_x = Q_0 - Q$, where Q_0 is the ground state to ground state Q-value [23], are then obtained. A two-dimensional plot correlating these two quantities is shown in Fig. 3. The acceptance reduction at high excitation energy and small scattering angles is due to the screens mounted at the entrance of the FPD, as described in Sec. 2.

When dealing with very rare processes like the DCE reactions, another important parameter of the experimental measurements is the sensitivity. In particular, in Fig. 3 there are only two spurious counts (blue triangular points) in the region between −7 and −2 MeV. This corresponds to a sensitivity of 2 counts within 5σ confidence level in an energy range of 1 MeV. This value confirms the high significance of the obtained data.

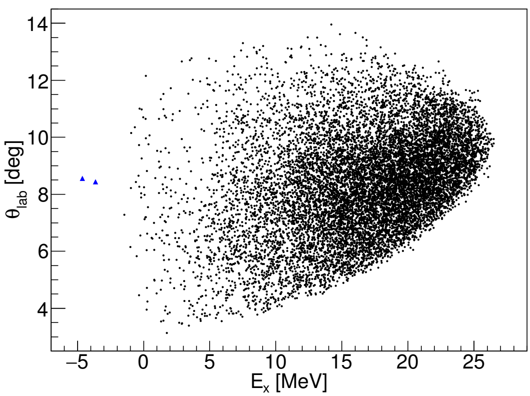

Fig. 3. $\theta_{\rm lab}$ *versus* E_x plot for the $^{20}O^{8+}$ events. Blue triangular points indicate spurious counts.

4. Summary

The ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn reaction has been measured for the first time. The data reported here show that the DCE measure with heavy ions has been successful: the experimental setup adopted, PID and ray-reconstruction procedures led to an excellent signal-to-noise ratio. As a consequence, it was demonstrated that the experimental difficulties that limited in the past the investigations of double charge-exchange reactions may be overcome.

REFERENCES

[1] S. Dell'Oro *et al.*, *Adv. High Energy Phys.* **2016**, 2162659 (2016).

[2] J. Barea, J. Kotila, F. Iachello, *Phys. Rev. C* **91**, 034304 (2015).

[3] J.D. Vergados, H. Ejiri, F. Simkovic, *Rep. Prog. Phys.* **75**, 106301 (2012).
[4] J. Engel, J. Menèndez, *Rep. Prog. Phys.* **80**, 046301 (2017).
[5] F. Cappuzzello *et al.*, *J. Phys.: Conf. Ser.* **630**, 12018 (2015).
[6] C. Agodi *et al.*, *Nucl. Part. Phys. Proc.* **265–266**, 28 (2015).
[7] F. Cappuzzello *et al.*, *Eur. Phys. J. A* **52**, 167 (2016).
[8] F. Cappuzzello *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **763**, 314 (2014).
[9] A. Cunsolo *et al.*, *Eur. Phys. J.: Spec. Top.* **150**, 343 (2007).
[10] F. Cappuzzello *et al.*, *Nature Commun.* **6**, 6743 (2015).
[11] D. Pereira *et al.*, *Phys. Lett. B* **710**, 426 (2012).
[12] D. Carbone *et al.*, *Phys. Rev. C* **90**, 064621 (2014).
[13] V. Soukeras *et al.*, *Phys. Rev. C* **91**, 057601 (2015).
[14] F. Cappuzzello *et al.*, *Eur. Phys. J. A* **51**, 145 (2015).
[15] M. Cavallaro *et al.*, *Eur. Phys. J. A* **48**, 59 (2012).
[16] D. Carbone *et al.*, *Eur. Phys. J. Plus* **130**, 143 (2015).
[17] F. Cappuzzello *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **621**, 419 (2010).
[18] K. Makino, M. Berz, *Nucl. Instrum. Methods Phys. Res. A* **558**, 346 (2006).
[19] A. Lazzaro *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **591**, 394 (2008).
[20] A. Lazzaro *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **585**, 136 (2008).
[21] A. Lazzaro *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **602**, 494 (2009).
[22] A. Lazzaro *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **570**, 192 (2007).
[23] F. Cappuzzello, D. Carbone, M. Cavallaro, *Nucl. Instrum. Methods Phys. Res. A* **638**, 74 (2011).