Załącznik nr 3

Scientific Curriculum Vitae (*Autoreferat*)

Studies of astrophysically-relevant nuclei around ^{78}Ni

Chiara Mazzocchi

Nuclear Physics Division of the Institute of Experimental Physics,

Faculty of Physics, University of Warsaw

Contents

1 NAME AND SURNAME

Chiara Mazzocchi

2 QUALIFICATIONS

- July 18th, 2002: Doctoral degree in Natural Sciences (*Doktor der Naturwissenschaften*) at University of Mainz (Johannes Gutenberg - Universität Mainz), Mainz, Germany. PhD thesis: "*Decay studies of nuclei near the proton drip-line*". Supervisor Prof. Ernst Roeckl.

- October 13th, 1998: University Degree in Physics (*Laurea in Fisica*) at University of Milan (Università degli Studi di Milano), Milan, Italy. Thesis title: "*Il decadimento esotico del* ^{242}*Cm per emissione di cluster di silicio*" (Exotic decay of ^{242}Cm through emission of silicon clusters). Supervisor Prof. Roberto Bonetti.

3 WORK EXPERIENCE

- Since January 2011: Assistant professor (*adiunkt*) at the Faculty of Physics, University of Warsaw, Poland.
- October 2010 – December 2010: University teacher at the Faculty of Physics, University of Warsaw, Poland.
- November 2006 – September 2010: Post-Doc (*assegno di ricerca*) at the Department of Physics, University of Milan, Milan, Italy.
- September 2003 – October 2006: Post-Doc at the Department of Physics and Astronomy, University of Tennessee, Knoxville-TN, USA.
- July 2002 – May 2003: Post-Doc at Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany.
- June 1999 – July 2002: PhD Student at GSI-Darmstadt and University of Mainz, Mainz, Germany.
- October 1998 – May 1999: Scientific collaborator at the Institute for Applied General Physics (IFGA) of the University of Milan, Milan, Italy.
- 2007 – 2015: Several extended stays (from 1 week up to 1 month) at major international laboratories, such as Oak Ridge National Laboratory and National Superconducting Cyclotron Laboratory at Michigan State University - USA, GSI-Darmstadt - Germany, CERN-ISOLDE - Switzerland, Institut Laue-Langevin in Grenoble - France, Japanese Atomic Energy Agency in Tokai - Japan, JINR-Dubna - Russia.

3.1 SCHOLARSHIPS

- June 1999 - May 2001: Scholarship granted by the University of Milan, for a training period in experimental nuclear physics at GSI - Darmstadt, Germany.

4 RESEARCH AND RESULTS RELATED TO THE HABILITATION TOPIC. ACHIEVEMENTS RESULTING FROM ART. 16 PAR. 2 OF THE ACT OF MARCH 14^{th}, 2003 ON ACADEMIC DEGREES AND SCIENTIFIC TITLE ON SCIENTIFIC DEGREES AND TITLES IN THE FIELD OF ART (DZ. U. NO. 65, ITEM 595 AS AMENDED).

4.1 HABILITATION TOPIC - TITLE.

Studies of astrophysically-relevant nuclei around ^{78}Ni.

4.2 PUBLICATIONS SELECTED FOR THE HABILITATION PROCESS.

A) **C. Mazzocchi**, R. Grzywacz, J.C. Batchelder, C.R. Bingham, D. Fong, J.H. Hamilton, J.K. Hwang, M. Karny, W. Królas, S.N. Liddick, A.F. Lisetskiy, P.F. Mantica, A.C. Morton, W.F. Mueller, K.P. Rykaczewski, M. Steiner, A. Stolz and J.A. Winger,
"*Low energy structure of even-even Ni isotopes close to ^{78}Ni*",
2005, Phys. Lett. B **622**, 45.

B) **C. Mazzocchi**, K.P. Rykaczewski, R. Grzywacz, P. Bączyk, C. Bingham, N.T. Brewer, C.J. Gross, C. Jost, M. Karny, A. Korgul, M. Madurga, A.J. Mendez II, K. Miernik, D. Miller, S. Padgett, S.V. Paulauskas, D.W. Stracener, M. Wolińska-Cichocka,
"*β-decay properties of the very neutron-rich isotopes ^{86}Ge and ^{86}As*",
2015, Phys. Rev. C. **92**, 054317.

C) **C. Mazzocchi**, R. Surman, R. Grzywacz, J.C. Batchelder, C.R. Bingham, D. Fong, J.H. Hamilton, J.K. Hwang, M. Karny, W. Królas, S.N. Liddick, P.F. Mantica, A.C. Morton, W.F. Mueller, K.P. Rykaczewski, M. Steiner, A. Stolz, J.A. Winger and I.N. Borzov,
"*New half-lives of very neutron-rich iron isotopes*",
2013, Phys. Rev. C **88**, 064320.

D) **C. Mazzocchi**, K.P. Rykaczewski, A. Korgul, R. Grzywacz, P. Bączyk, C. Bingham, N.T. Brewer, C.J. Gross, C. Jost, M. Karny, M. Madurga, A.J. Mendez II, K. Miernik, D. Miller, S. Padgett, S.V. Paulauskas, D.W. Stracener, M. Wolińska-Cichocka and I.N. Borzov,
"*New half-life measurements of the most neutron rich arsenic and germanium isotopes*",
2013, Phys. Rev. C **87**, 034315.

E) **C. Mazzocchi**, R. Grzywacz, J.C. Batchelder, C.R. Bingham, D. Fong, J.H. Hamilton, J.K. Hwang, M. Karny, W. Królas, S.N. Liddick, P.F. Mantica, A.C. Morton, W.F. Mueller, K.P. Rykaczewski, M. Steiner, A. Stolz and J.A. Winger,
"*Beta-delayed γ-and neutron emission near the double shell closure at ^{78}Ni*",
2005, Eur. Phys. J. A**25**, s01, 93.

F) **C. Mazzocchi**, A. Korgul, K.P. Rykaczewski, R. Grzywacz, P. Bączyk, C.R. Bingham, N.T. Brewer, C.J. Gross, C. Jost, M. Karny, M. Madurga, A.J. Mendez II, K. Miernik, D. Miller, S. Padgett, S.V. Paulauskas, D.W. Stracener, M. Wolińska-Cichocka,
"*Beta decay of the most neutron-rich isotopes close to ^{78}Ni*",
2015, Acta Phys. Pol. B**46**, 713.

From here on, publications selected for the habilitation process will be referred to as A), ..., F), respectively.

4.3 Physics motivations and results

Motivations The region of the chart of nuclei around ^{78}Ni has attracted large attention in the last $10-15$ years. Still, it remains rather elusive. On the one hand, several experimental studies provided evidence that this is clearly a doubly-magic nucleus, yet, this is also a region where transitions to deformed phenomena have been reported. Theoretical models for nuclei in this corner of the chart of nuclei predict that the large neutron excesses in the nuclear system can affect the nucleon-nucleon interaction and result in changes to traditional shell gaps and magic numbers. Such phenomena may originate from particular effects of the residual interaction for a very asymmetric proton-neutron system 1). The renewed experimental interest in this region has largely been driven by the developments of stronger beam intensities achieved at fragmentation facilities and at ISOL-based laboratories. Exploratory studies are becoming more and more difficult at present-day facilities and require new generation radioactive beam facilities, most of which are still under development. Hence,

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1) T. Otsuka et al., Eur. Phys. J. A 13 (2002) 69.

the focus of today experiments needs to be on in-depth studies, in order to increase the understanding of the physics involved.

New experimental data on such exotic nuclei allow to probe the predictive power of theoretical calculations. Close to the double shell closure at N=50 and Z=28, shell-model calculations are normally employed to explore the nuclear structure of such exotic nuclei. One difficulty in the shell-model description of nuclei with $N \leq 50$ and $Z \leq 28$ lies in the large number of valence neutrons in the fpg model space. The complexity of such calculations 2),3),4),5) makes the experimental verification even more important. The neighbourhood near doubly magic ^{78}Ni provides benchmark nuclei for probing the theoretical predictions. For this purpose, information on both structure and gross properties of isotopes approaching N=50 and Z=28 with large N/Z ratios is crucial.

In even-even nuclei close to double shell closures, the sequence of yrast levels can be explained as a simple consequence of the short-range nature of the nuclear interaction. Nuclei that can be described by a system of two identical particles/holes in a high-j orbital in the nuclear potential well outside the closed shell, should be characterised by a similar energy spectrum, with maximum spin J=2j−1. Microsecond isomers are originated by the near degeneracy of the J and J−2 levels and their appearance is a signature of shell closure. In the magic Z=28 nickel isotopes the occupation of the $\nu g_{9/2}$ orbital leads to the generation of such yrast-isomers with a simple configuration and $J^{\pi}=8^{+}$. Similar isomers are observed also the N=50 valence mirror nuclei the ^{100}Sn region, where protons fill the $\pi g_{9/2}$ orbital 6). Hence the appearance of 8^{+} isomers even-even nickel nuclei with $40<N<50$ is expected and supported by systematics. Insight into low-energy structure of nickel isotopes can be gained not only by isomer-spectroscopy, but also by investigating the β decay of neutron-rich cobalt isotopes. See publication A) for details.

If studying and understanding the nickel isotopes structure is crucial for supporting the magicity of ^{78}Ni, the investigation of nuclei with $N > 50$ and $Z > 28$ allows to probe the limits of the predictive power of theoretical calculations when valence nucleons are added to the ^{78}Ni core. This is illustrated in publications B) and F).

The neighbourhood of ^{78}Ni is of interest not only for nuclear structure but also for nuclear astrophysics because of its relevance for the rapid-neutron-capture (r-) process modelling, being situated at the beginning of the path that it is predicted to follow. The r-process, which results from explosive stellar events, involves multiple captures of neutrons on iron nuclei close to ^{78}Ni. These captures continue until β decay occurs, with the consequent change of atomic number, followed by more neutron captures, subsequent β decay, etc. It is considered to be responsible for the creation

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[2] K. Langanke et al., Phys. Rev. C 63 (2001) 032801(R)

[3] T. Otsuka et al., Acta Physica Polonica 36 (2005) 1213.

[4] T. Papenbrock et al., Phys. Rev. C 69 (2004) 024312

[5] K. Sieja and F. Nowacki, Phys. Rev. C 81, 061303(R) (2010)

[6] R. Grzywacz et al., Phys. Lett. B 355 (1995)439.

of about half of the nuclei that are heavier than iron [7),8),9)], yet the astrophysical site where it occurs has still to be determined. Nevertheless, it is certain that the *r*-process path includes neutron capture and β decay of nuclei very far from stability, much beyond the current experimental knowledge. Since it is not possible to measure in the laboratory the needed gross properties, such as mass, half-life and β-delayed neutron (βn) probability for the hundreds of nuclei involved the process, most of which are still unknown or at present too exotic to reach experimentally, reliable theoretical predictions need to be employed. The removal of nuclear physics uncertainties from the *r*-process model should allow one to better discriminate between various models which involve different physical conditions, see publications C), D) and E).

The models commonly used in network calculations, such as those predicting the *r*-process path, are global models. The pioneer in this respect has been the gross theory of β decay. Later, the finite-range droplet model (FRDM) with the addition of quasiparticle random-phase approximation (QRPA) for the Gamow-Teller (*GT*) part with an empirical spreading for the quasiparticle strength and the gross-theory to describe the first forbidden transitions (FRDM+QRPA) [10)], has become the most widely used model to calculate ground-state properties of a wide range of very neutron-rich nuclei: the theoretical values of β decay half-lives commonly implemented *r*-process simulations use the latter calculations, which differ from the measured values by at least a factor of five. More recently, a microscopic model was developed to self-consistently calculate ground-state properties, *GT* and first-forbidden transitions of neutron-rich nuclei. It is based on energy density functional plus continuum QRPA (CQRPA) approximation [11)] and was used, together with the new DF3a energy density functional [12)] optimised for neutron-rich isotopes in the vicinity of N=50 and N=82, to predict the half-lives of very neutron-rich zinc and gallium isotopes. *R*-process calculations performed with this model showed a significant improvement in the predicted isotopic abundances for A>140, with values much closer to those obtained from observation [13)]. As far as the production of lighter nuclei ($A\sim80$) is concerned, the astrophysical conditions that produce them are also particularly uncertain [14)]. They are believed to be produced in the so-called weak *r*-process nucleosynthesis [15)]. Simulations for this process are further complicated by uncertainties in the nuclear physics properties of the very unstable nuclei that participate in it. See publications C), D) and E) for details.

The problematic discussed above was addressed by the series of publications constituting the basis for the habilitation process. The disappearance and reappearance

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[7] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547 (1957).

[8] M. Arnould, S. Goriely, and K. Takahashi, Phys. Rep. 450, 97 (2007).

[9] K. Langanke and G. Martńez-Pinedo, Rev. Mod. Phys. 75, 819 (2003).

[10] P. Möller et al., Phys. Rev. C 67 (2003) 055802.

[11] I.N. Borzov, Phys. Rev. C 67 (2003) 025802.

[12] S.V. Tolokonnikov and E.S. Saperstein, Phys. At. Nucl. 73 (2010) 1684.

[13] M. Madurga,..., C. Mazzocchi, ..., Phys. Rev. Lett. 109 (2012) 112501.

[14] A. Arcones and F. Montes, Astrophys. J. 731, 5 (2011).

[15] R. Surman et al., Astrophys. J. 679 (2008) L117

of the 8^+ isomers in ^{72,74,76}Ni was verified and explained (see publication A)), the low energy structure of nickel isotopes was investigated by means of β decay of the respective cobalt precursors (see publication A)), the low-energy structure of ^{86}As produced the β decay of ^{86}Ge was measured for the first time and that of its β-daughter measured with much improved results with respect to literature (see publications B) and F)). Half-lives of the very neutron-rich ^{72}Fe, $^{71-74}$Co, $^{84-86}$Ge and $^{84-87}$As were measured for the first time (^{72}Fe, ^{74}Co and ^{86}Ge) or with improved accuracy ($^{71-73}$Co, ^{84,85}Ge and $^{84-87}$As), see publications A), C) and D). Beta-delayed neutron probabilities of $^{71-74}$Co were measured for the first time (see publication E)).

Results. Within the scientific context described above, the aim of the present work was the characterisation of nuclear properties in the neighbourhood of ^{78}Ni. The relevant radioactive-beam experiments were performed at world-leading facilities, such as the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (East Lansing, MI, USA) and the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (Oak Ridge, TN, USA). In these laboratories different production (fragmentation reactions and fission, respectively) and separation methods (in-flight separation and ISOL) for exotic nuclei are used.

The production method for the isotopes to investigate, hence the facility where to perform the experiments, were selected in order to have the best possible experimental conditions (radioactive beam intensity, purity and high-efficiency detection set-ups). Since isotopes with $Z<28$ are characterised by very low yields if produced in fission of a heavy target (like ^{238}U), ^{72}Fe, $^{71-74}$Co and ^{76}Ni were produced in projectile fragmentation of a 140 A·MeV ^{86}Kr beam on a thick ^{9}Be target and separated by means of the A1900 Fragment Separator at the NSCL. See publications A), C) and E) for details. On the other hand, germanium and arsenic isotopes in the $A\sim80$ fission-peak region are produced with much higher yield in fission than in fragmentation. For this reason, proton-induced fission of ^{238}U was employed to study the β decay of $^{84-86}$Ge and $^{84-87}$As at the HRIBF. There, the coupling of ion source chemistry and two-stage electro-magnetic separation provided almost pure, very neutron-rich radioactive beams. The proton beam impinged on a $^{238}\mathrm{UC}_x$ target inside the ion source to which H_2S gas was added to suppress contaminants: the ^{A}Ge and ^{A}As isotopes diffusing out of the target material formed $^{A}\mathrm{Ge}^{32}\mathrm{S}^+$ or $^{A}\mathrm{As}^{32}\mathrm{S}^+$ molecules, respectively, while contaminant bromine and selenium isotopes do not form sulphide molecules. In the first stage of mass separation, mass A+32 was selected, suppressing mass A contaminants. After going through a charge-exchange cell which broke the molecule, mass A was selected in the second stage, suppressing mass A+32 contaminants (i.e. silver isotopes, produced in abundance in fission). See publications B), D) and F) for details.

In both laboratories very efficient detection set-ups were employed. At the NSCL the radioactive beam was implanted into a double sided silicon-strip detector (DSSSD) surrounded by the SeGA array of germanium detectors. Correlation in space and time between the implanted ion and the subsequent β decay allowed to impose a gate on the γ

spectra from the SeGA array and obtain very clean γ-ray spectra. At the HRIBF, the purified radioactive beam was implanted into a moving tape collector, which periodically moved the activity away from the measuring spot. The implantation point was surrounded by two plastic scintillators for β-counting and four clover high-purity germanium detectors in close geometry.

The search for microsecond isomers in even-even nickel nuclei and for the structure of low-lying states in nickel isotopes was performed at the NSCL. For the first time four γ transitions were assigned to the decay of the $J^\pi=8^+$, $T_{1/2}=590^{+180}_{-110}$ ns isomer in ^{76}Ni, thus establishing the $0^+-2^+-4^+-6^+-8^+$ ground-state band. No such isomer was observed in the ^{72,74}Ni isotopes. Nevertheless, the low-energy structure of the latter two isotopes was reinvestigated using β decay of ^{72,74}Co to populate low-energy states in them. The previously known decay scheme of ^{72}Co [16)] was confirmed by means of $\beta-\gamma-\gamma$ coincidences and the previously unknown 2^+ and 4^+ levels belonging to the ground-state band in ^{74}Ni were identified in the β decay of ^{74}Co. The observed levels were compared to shell-model calculations using two different residual interactions, namely S3V [17)] and NR78 [18)], see publication A) for details. Calculations with S3V predict 8^+ isomers for the even $^{70-76}$Ni isotopes, as well as for ^{78}Zn, with the dominant component of the wave function being the $(g_{9/2})^2$ neutron pair excitations. These calculations, however, did not agree with the experimental data [16)]. The empirical adjustment of the NR78 residual interaction [18)] describes the experimental data for ^{72}Ni and ^{74}Ni.

In Figure 1 the energy systematics of the lowest-lying excited states in even-even nuclei from experiment and predictions from both shell models are plotted. The existence of the ^{76m}Ni $J^\pi=8^+$ isomer with its 144 keV $E(8^+)-E(6^+)$ energy gap and small $B(E2, 8^+\rightarrow 6^+)=0.7^{+0.2}_{-0.1}$ W.u. points to high purity of the $J=6$ and $J=8$ states and hence indicates a good $N=50$ shell closure at ^{78}Ni. Theoretical calculations performed with the NR78 interaction reproduce well the experimental values for the 2^+ and 4^+ states in $^{70-76}$Ni. The same calculations offer an explanation for the disappearance of the 8^+ isomer in ^{72,74}Ni. The lowering of the 6^+_2 state with two broken $g_{9/2}$ neutron pairs (seniority $\nu=4$) below the 8^+_1 ($\nu=2$) state, at almost degenerate energy with the 6^+_1 ($\nu=2$) level, opens a second and faster deexcitation channel for the 8^+_1 state. In the S3V interaction this state lies about 200 keV above the isomer (see Figure 1). See publication A) for details. Following this work, I co-proposed [19)] and proposed [20)] two experiments to continue these studies on nickel nuclei with even larger N/Z ratios. The former one led to extended information on low-lying excited states in ^{71,73}Ni [21)]

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[16] M. Sawicka et al., Phys. Rev. C 68 (2003) 044304.

[17] H. Grawe, Nucl. Phys. A704 (2002) 211c.

[18] A.F. Lisetskiy et al., Phys. Rev. C 70 (2004) 044314.

[19] "Neutron single-particle states and β-delayed neutron branching ratios near ^{78}Ni", proposal number E05020 at NSCL (MSU), 2005.

[20] "Identification of excited states in ^{75}Ni", proposal number E10027 at NSCL (MSU), 2010.

[21] M.M. Rajabali, R. Grzywacz, S.N. Liddick, C. Mazzocchi, ..., Phys. Rev. C **85** 2012 034326.

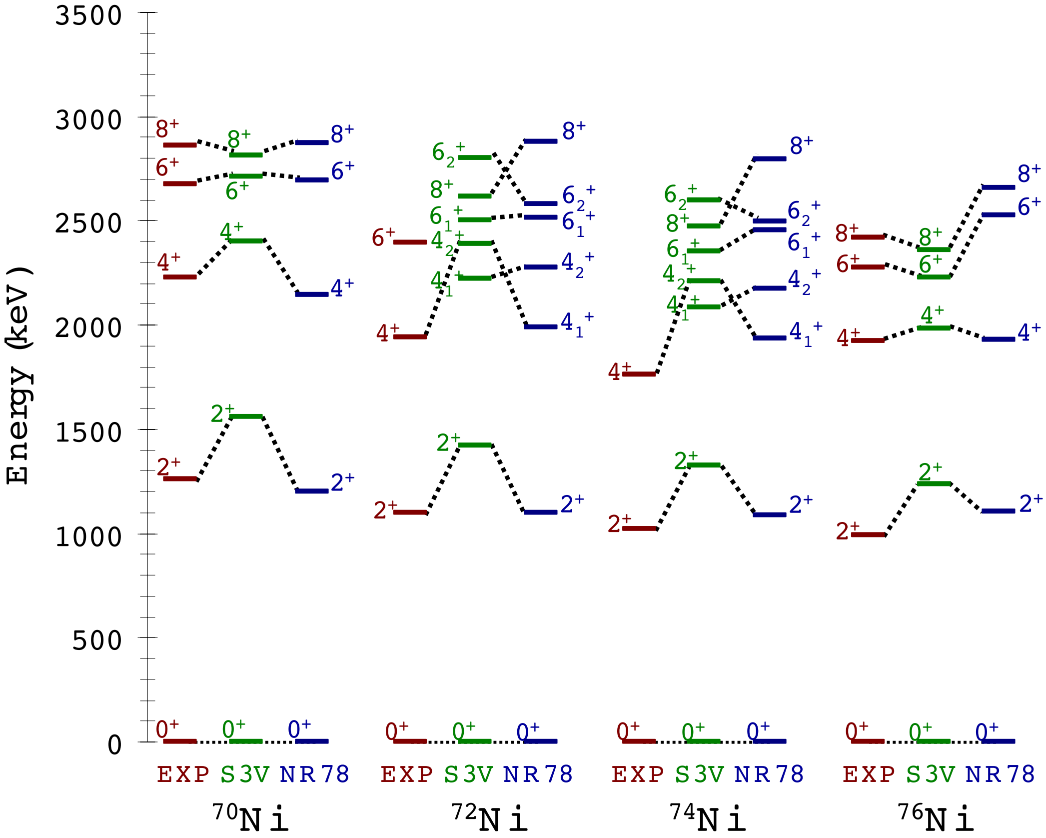

Figure 1: Energy systematics of the lowest-lying excited states in even-even nickel nuclei from experiment (EXP) and shell-model calculations with realistic two-body matrix elements (S3V [17] and NR78 [18]).

and ^{72}Ni [22], while the second one, performed in 2014 and currently under analysis, aimed at the first measurement of excited states in ^{75}Ni to be produced in the β decay of ^{75}Co.

In order to investigate how nuclear properties change when departing from the Z=28 shell closure, I proposed an experiment to study the decay of ^{86}Ge [23]. The β decay properties of the very neutron rich nucleus ^{86}Ge and of its daughter ^{86}As were measured at the HRIBF. Information on β-decay properties of ^{86}Ge and on excited states in ^{86}As was obtained for the first time. Spectroscopic information on excited states in ^{86}Se was

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[22] M.M. Rajabali, R. Grzywacz, S.N. Liddick, C. Mazzocchi, ..., J. Phys. G: Nucl. Part. Phys. **41** (2014) 115104.

[23] "Decay spectroscopy of accelerated beam components: A test of the sensitivity of the ranging-out technique - Half-life measurement of ^{86,87}Ge", proposal number RIB128 at HRIBF (ORNL), 2004.

largely extended. Part of the data analysis has been performed within the framework of the Master Thesis of Paweł Bączyk at FUW under my supervision [24]. The results were interpreted within an advanced shell model approach. These calculations, previously explaining well the structure of ^{84}Ge and ^{85}Ge, were not able to reproduce all experimentally determined features of measured level schemes of ^{86}As and ^{86}Se, pointing towards problems with the interaction when more protons and neutrons are added to the ^{78}Ni core. The Gamow-Teller (GT) decay of ^{86}Ge and ^{86}As was also investigated in a shell-model framework. These very neutron-rich isotopes were characterised by large Q_β decay-energy window and low neutron separation energy (S_n) threshold in the daughter nuclei. Their allowed GT decays will proceed only between fpg neutrons and the respective spin/orbit partner proton orbitals, in the single-particle limit: valence neutrons, occupying the $d_{5/2}$ and $s_{1/2}$ orbitals, cannot undergo GT decay because of the limited Q_β value. Since the fpg neutron states that participate in the decay are very deeply bound, the GT decay transformation will populate mostly highly excited states in the decay daughter. The lower-lying states will be fed in forbidden decays. The results of the theoretical calculations, compared to the experimental results obtained in this work, showed that a new set of interactions needs to be developed and highlighted the important role played by the proton-neutron residual interactions in describing these very neutron-rich isotopes. See publications B) and F) for details.

A significant achievement of this scientific program is the study of the β-decay ground-state properties of several neutron-rich nuclei below and above ^{78}Ni. Neutron-rich iron and cobalt nuclei were produced in projectile fragmentation at the NSCL as described above. The half-lives of ^{72}Fe ($T_{1/2}$=19±4 ms) and ^{74}Co ($T_{1/2}$=30±3 ms) could be measured for the first time, while those of $^{71-73}$Co and $^{69-71}$Fe were remeasured with improved statistics and accuracy. Neutron-rich germanium and arsenic isotopes were investigated at the HRIBF, where fission was the production mechanism of choice. The half-life of ^{86}Ge ($T_{1/2}$=226±21 ms) was determined for the first time, while those of ^{84,85}Ge and $^{84-87}$As were remeasured. The values for ^{69,70}Fe, ^{71,72}Co and ^{84,85}Ge and $^{84-87}$As are generally in a good agreement with the previous values from literature (NNDC [25]), with a more precise value measured in this work for ^{71}Fe, ^{73}Co, ^{85}Ge and ^{87}As decay, respectively, see publications C) and D). The results are compared to theoretical predictions of gross theory of β decay, of the FRDM+QRPA model and of new calculations using the DF3a+CQRPA model, see Figure 2.

In the case of nuclei beyond the Z=28 and N=50 shell closures, gross theory systematically overestimates the β-decay rate by up to an order of magnitude, while QRPA-based models provide a better agreement between predictions and measured half-lives. Among these latter models, the DF3a+CQRPA gives the best estimates for the half-lives, in particular for zinc, gallium [13] and germanium isotopes, and it is less accurate for arsenic isotopes. In the case of the iron isotopes the FRDM+QRPA

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[24] P. Bączyk, "*Beta decay of very neutron-rich germanium isotopes*", Master thesis, University of Warsaw, 2013 (in English)

[25] www.nndc.bnl.org

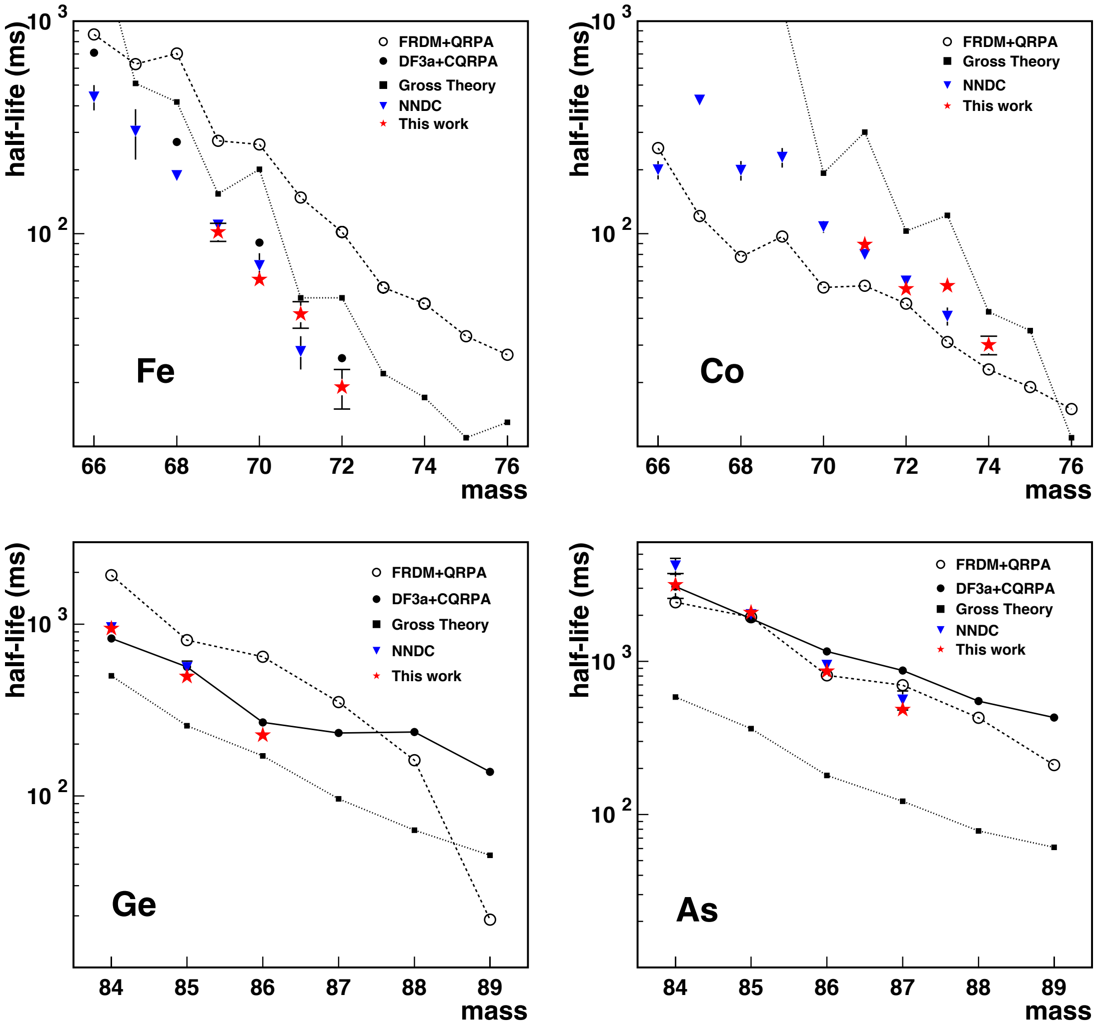

Figure 2: Halflives for neutron-rich iron, cobalt, germanium and arsenic isotopes. Experimental results from this work (red stars) are compared to literature (NNDC [25], blue triangles), where available, and to theoretical predictions from the FRDM+QRPA [10] (empty circles), DF3a+CQRPA [11], [12] (full circles) and gross theory (full black squares). Lines are used to guide the eye in the case of theoretical predictions.

model overestimates the half-lives by up to one order of magnitude. On the contrary, the DF3a+CQRPA calculations confirmed their good predicting power for the half-lives of very neutron rich nuclei in the ^{78}Ni region also below the Z=28 and N=50 shell closures. As far as the cobalt isotopes are concerned, the FRDM+QRPA and gross theory underestimate and overestimate, respectively, the half-lives by a factor 2−3. The new half-life values of ^{72}Fe and ^{86}Ge provide additional validation of DF3a+CQRPA, which has therefore proven to be rather robust. This systematic study of the predictive power of several theoretical calculations for ground state properties of exotic nuclei suggests that further improvements need to be implemented, as well as the development of the next-generation models, in order to have the same quality predictions for nuclei close to the N=50 shell closure and for those further from magic gaps.

The most robust of the calculations available and discussed here, namely the DF3a+CQRPA model, have already been used as input parameters in the calculations to predict the r-process abundances, showing a significant impact on the predicted abundances for A>140, with values much closer to the measurements with respect to the same calculations performed using FRDM+QRPA input data 13). The potential impact of the new decay rates for iron isotopes on simulations of weak r-process nucleosynthesis, which is responsible for the production of the lighter (A∼80) nuclei, was also analysed. The uncertainties in the theoretical decay rates of $^{69-72}$Fe not only lead to uncertainties in the predicted abundances of these isotopes, but also translate to large uncertainties throughout the abundance pattern. An example weak r-process calculation was run using the set of nucleosynthesis codes described in Surman *et al.* 15) and a parametrised neutrino wind, similar to the astrophysical conditions from that work, that produces a reasonable match to the solar r-process abundance pattern in the A∼80 region. The comparison of the simulation run with theoretical (FRDM+QRPA) β-decay rates for $^{69-72}$Fe with realistic typical uncertainties on them (factor five) and run with the experimental rates of the iron isotopes show a reduction in the uncertainties of the predicted r-process abundances. See publication C) for details.

The study of ground-state properties of neutron rich nuclei around ^{78}Ni included βn emission from $^{71-74}$Co. The first evidence for βn emission from very neutron-rich cobalt isotopes was obtained from the analysis of β-delayed γ rays ($\beta\gamma$) from decay of $^{71-74}$Co. The correlated $\beta\gamma$ spectra show not only transitions previously assigned to the β-decay daughter, but also transitions within the βn daughter. This allowed to set lower limits on the branching ratios for βn emission. See publication E) for details. To continue investigating βn emission in the region of the chart of nuclei just above ^{78}Ni, I proposed two experiments at ILL-Grenoble 26),27), which are in progress.

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26) "Measurement of β-delayed neutron properties of fission fragments", proposal number 3-01-584 at ILL Grenoble, 2011.

27) "Beta-delayed neutron properties of fission fragments", proposal number 3-01-594 at ILL Grenoble, 2011.

5 OTHER RESEARCH INTERESTS AND ACTIVITIES

5.1 RESEARCH INTERESTS BEFORE COMPLETION OF THE DOCTORAL STUDIES

Master studies. The diploma thesis work in experimental nuclear physics was conducted at the Institute for Applied General Physics (IFGA) of University of Milan in the group of Prof. Bonetti. The subject of the master thesis was the investigation of the phenomenon of cluster radioactivity, which consists in the spontaneous emission of heavy ions from nuclei in their ground state. In particular, the decay of ^{242}Cm by emission of $^{34}_{14}\mathrm{Si}_{20}$ to the doubly-magic ^{208}Pb was investigated both experimentally and theoretically. The ^{34}Si cluster emitted from ^{242}Cm constitutes to date the heaviest cluster emitted spontaneously from a nuclear ground-state. Such an exotic decay mode is very rare, with a branching ratio of 1×10^{-16} with respect to α decay and 6×10^{-8} with respect to spontaneous fission. Solid state nuclear track detectors were used in order to maximise the detection efficiency for the heavy clusters and minimise the background due to the overwhelming α and fission events. These detectors are characterised by having a threshold on the minimum charge that can be detected and at the same time maintaining a very large efficiency. A phosphate glass not sensitive to α particles was chosen. When the charged particle of high-enough Z interacts with the detector, a permanent damage to its molecular structure is caused (track). By means of chemical etching in an appropriate solution, the damaged track is enlarged to dimensions such that it can be observed and measured under an optical telescope.

The thesis work 28) involved the calibration and analysis of solid-state track detectors using a computer-governed microscope. The optimisation of the parameters used by this system was part of the thesis work as well as theoretical calculations to interpret the data 29), performed in collaboration with Prof. Raj K. Gupta from Panjab University, Chandigarh, India. The comparison of the theoretical calculations for the partial decay constant for this particular decay branch obtained with different models, shows that the study of the emission of such a heavy cluster can help to discriminate between the different theoretical approaches available (collective versus microscopic models): collective models seems to have a better predictive power for this decay mode.

After the Diploma, I collaborated with the IFGA to train the new master student in the group to the techniques used.

Doctoral studies. The PhD work concerned the study of the decay properties of the very exotic proton-rich nuclei in the neighbourhood of the doubly magic nu-

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[28] A.A. Ogloblin, ..., C. Mazzocchi, ..., Phys. Rev. C61 (2000) 034301.

[29] C. Mazzocchi *et al.*, Phys. Rev. C61 (2000) 047304.

clei ^{56}Ni and ^{100}Sn: β-decay of ^{50}Ni $^{30)}$ and ^{60}Ga $^{31)}$ and α decay of ^{114}Ba $^{32)}$. ^{60}Ga is the lightest bound gallium isotope and ^{114}Ba the lightest (experimentally) known barium isotope to date. The first spectroscopic information was obtained for ^{50}Ni and ^{60}Ga. In the case of ^{50}Ni this included half-life and delayed-proton energy spectrum and branching ratio. As for ^{60}Ga the energy spectrum and branching ratio for β-delayed protons and αs were obtained, as well as the half-life. The investigation of the β-delayed γ branch led to the identification of the Isobaric Analogue State in ^{60}Zn, which allowed the semi-empirical determination of the mass excess of ^{60}Ga by means of Coulomb-displacement energy systematics. Information on mass and half-life of ^{60}Ga are relevant for calculations of the astrophysical rapid proton capture (*rp*-) process.

The *rp*-process is supposed to be responsible for the nucleosynthesis of proton-rich isotopes of elements between iron and tellurium. If the half-life of a nuclide involved in the process is long, the process is slowed down at this point. Such nuclei are called "waiting points". The proton-separation energy (S_p) values of neutron-deficient gallium isotopes are of crucial importance for the *rp*-process as they determine at which zinc isotope (i) a captured proton is not removed right away by strong photo-disintegration of the weakly proton-bound gallium isotone and (ii) the *rp*-process can proceed to heavier elements via fast proton captures. In particular, they determine to which degree the β decay of the potential long-lived waiting point nucleus ^{60}Zn ($T_{1/2}$=2.4 min) can be bypassed by proton captures on ^{59}Zn or ^{60}Zn. This depends sensitively on the S_p values of ^{60}Ga and ^{61}Ga. Calculations assuming an S_p value close to the one determined in this work, have shown that because of the small S_p value of ^{60}Ga, only a small fraction of the *rp*-process flow runs through ^{60}Ga, while its dominant part involves the β-decay of ^{59}Zn.

The study of the decay of ^{114}Ba led to the discovery of its α-decay branch and of the successive decay chain ^{110}Xe$\rightarrow$^{106}Te$\rightarrow$^{102}Sn. The α-decay energy and branching ratio allowed to determine the Q-value and reduced α-decay width (W_α), showing indication of "super-allowed" character for the α-decay of ^{114}Ba. At the end of the PhD studies I co-proposed and experiment to continue the investigation of α decay in the ^{100}Sn region $^{33)}$. The results deepened the understanding of α-decay properties of ^{110}Xe and ^{106}Te $^{34)}$.

The nucleus ^{114}Ba was also a candidate for cluster radioactivity by emission of ^{12}C to ^{102}Sn. The decay probability for this exotic radioactivity strongly depends on the Q-value available. So far theoretical predictions, which span over a wide range, had to be employed to estimate this Q-value. The measurement of the α-decay of energy for the chain ^{114}Ba$\rightarrow$^{110}Xe$\rightarrow$^{106}Te$\rightarrow$^{102}Sn allowed to determine experimentally the Q-

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[30] C. Mazzocchi *et al.*, Eur. Phys. J. A17 (2003) 519.

[31] C. Mazzocchi *et al.*, Eur. Phys. J. A12 (2001) 269.

[32] C. Mazzocchi *et al.*, Phys. Lett. B532 (2002) 29.

[33] "*Alpha decay studies beyond ^{100}Sn*", proposal number U202 at the GSI-ISOL facility, 2002.

[34] Z. Janas, C. Mazzocchi, et al, Eur. Phys. J. A23 (2005) 197.

value for ^{12}C emission. The knowledge of its value allows to verify the theoretical models for the predictions of the partial half-life for such exotic decay mode.

During the graduate studies I could participate in most of the experiments performed at the GSI-ISOL- and in several measurements at the GSI-FRS facility, which applied different experimental techniques and investigated various nuclear structure aspects. All the experiments were performed within broad international collaborations. The participation in the experiments involved the preparation of the detection set-up with its electronics, its calibration and taking part in the data taking phase. In the measurements performed at the FRS, ion-optics simulations and tuning of the spectrometer were also involved.

5.2 RESEARCH INTERESTS AFTER COMPLETION OF THE DOCTORAL STUDIES

Studies of nuclear structure in the neighbourhood of ^{100}Sn. In the region of the chart of nuclides just above ^{100}Sn, an island of α and proton radioactivity exists. Its presence is due to the simultaneous vicinity to the proton drip-line and to the double shell closure N=Z=50. The investigation of these decay modes allows to obtain information on the wave function of the nuclear states involved in the transitions. Moreover, the energy of the emitted particles, corrected for the recoil effects of the daughter nucleus, permits to determine the mass or mass excess of the parent and/or daughter nucleus, if the other one is known. Around ^{100}Sn, just above it, valence protons and neutrons happen to be in the same orbitals ($d_{5/2}$ and $g_{7/2}$) and their correlations can be investigated. An enhancement of the α-particle preformation probability is expected to originate the so-called “super-allowed α decay”. I contributed to intensive studies on such nuclei, which led to the discovery of the new isotopes ^{109}Xe and ^{105}Te [35)] and to the measurement of the α-decay chain ^{109}Xe→^{105}Te→^{101}Sn [35)]. The ^{109}Xe mother nuclei were produced in the ^{54}Fe(^{58}Ni,3n) fusion-evaporation reaction and separated from the other reaction products by means of the Recoil Mass Spectrometer (RMS) at the HRIBF, ORNL. The recoils were implanted into a DSSSD at the focal plane of the spectrometer, with read-out performed entirely though pioneering digital electronics with innovative readout [36)]. As a result, the half-lives of the two hitherto unknown decays were determined [35)] (13±2 ms and 620±70 ns for ^{109}Xe and ^{105}Te, respectively). Together with the Q$_\alpha$ values, they allowed to determine W$_\alpha$ for the two nuclei. An enhancement was observed in W$_\alpha$(^{105}Te) with respect to that of the polonium nucleus having the same valence structure (W$_\alpha$(^{213}Po)) of a factor 2.7, indicating the super-allowed character of the α decay of ^{105}Te. Moreover the observation of fine structure in the α decay of ^{109}Xe allowed to determine the energy of the first excited

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[35] S.N. Liddick, R. Grzywacz, C. Mazzocchi, et al., Phys. Rev. Lett. 97 (2006) 082501

[36] R. Grzywacz,..., C. Mazzocchi,..., Nucl. Instr. and Meth. in Phys. Research B261 (2007) 1103.

state in ^{105}Te. In a follow-up experiment fine structure was observed also in the α decay ^{105}Te$\rightarrow$^{101}Sn, allowing to set the spin/parity of ^{101}Sn ground state as $(7/2^{+})$ [37]. This is due to the lowering of the $\nu g_{7/2}$ with respect to the $\nu d_{5/2}$ when removing two neutrons going from ^{103}Sn to ^{101}Sn.

The measurement of half-lives and masses in this region of the nuclidic chart has the added value of being relevant to nucleosynthesis. In fact, it was predicted for the astrophysical *rp* process to terminate in a cycle around Sn−Sb−Te isotopes close to ^{100}Sn [38]. Half-lives and masses are extremely important input parameters for astrophysical network calculations: different values provided by different theoretical calculations could influence the path followed in the final phase of the *rp* process during a supernova explosion. In particular, S_p in ^{105}Sb, which lies within the Sn−Sb−Te cycle, constituted a puzzle. The nuclide ^{105}Sb was reported to be a proton emitter [39] with a Q-value Q_p=$-S_p$=483±15 keV, but despite many attempts applying various techniques over the following 20 years the result could not be confirmed by direct observation of proton emission [40],[41],[42],[43],[44],[45]. A different approach needed to be followed in order to clarify the situation. The result on the S_p value for ^{105}Sb can in fact be verified by measuring the expected small α-decay branch of ^{109}I, which is predominantly a proton emitter having a half-life of 100±5 μs. A measurement of the ^{109}I α-decay energy would allow an indirect and independent determination of S_p in ^{105}Sb, since $Q_\alpha(^{109}\mathrm{I})+Q_p(^{105}\mathrm{Sb})=Q_p(^{109}\mathrm{I})+Q_\alpha(^{108}\mathrm{Te})$. The experiment was carried on at the RMS at the HRIBF with a technique similar to the one successfully applied to the discovery and study of the decay of ^{109}Xe. The observation of the minuscule α-decay branch of ^{109}I ($(1.4\pm0.4)\cdot10^{-4}$) allowed, together with the experimental measurement of its decay energy, to fix independently the value of $Q_p(^{105}\mathrm{Sb})$ as 356±22 keV [46]. The fact that ^{105}Sb is more proton-bound than previously reported rules out the possibility of a measurable proton-decay branch from this nucleus. This measurement permitted also to set an upper limit for $Q_p(^{104}\mathrm{Sb})$ ($Q_p(^{104}\mathrm{Sb})<378$ keV). From the astrophysics perspective, the new Q_p value of ^{105}Sb excludes the formation of a Sn−Sb−Te cycle at ^{104}Sn and the corresponding enhancement in energy production and X-ray luminosity during the tail end of an X-ray burst. However, if the new limit for $Q_p(^{104}\mathrm{Sb})$ is taken into account and if the value is much lower than this upper limit, such an enhancement would be a possibility by means of the formation of a cycle

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[37] I.G. Darby et al., Phys. Rev. Lett. 105 (2010) 162502

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[39] R. Tighe et al., Phys. Rev. C 49 (1994) R2871.

[40] M. Shibata et al., Phys. Rev. C 55 (1997) 1715.

[41] Z. Liu, ..., C. Mazzocchi, ..., Phys. Rev. C 72 (2005) 047301.

[42] G. Berthes, GSI Report No. GSI-87-12, 1987, p. 80 - 89.

[43] J. Friese, Proceedings of the XXIV Hirschegg Workshop (GSI Report ISSN 0720-8715, 1996), p. 123.

[44] K. Rykaczewski et al., Phys. Rev. C 52 (1995) R2310.

[45] A. Gillitzer et al., Z. Phys. A 326 (1987) 107.

[46] C. Mazzocchi et al., Phys. Rev. Lett. 98 (2007) 212501.

at ^{103}Sn if the ^{104}Sb(p,γ)^{105}Te reaction rate is strongly underestimated. My contribution to this project consisted in contribution to the preparation of the experimental set-up, in the analysis of the collected data and in the preparation of the manuscript 46).

In order to clarify whether the Sn−Sb−Te cycle can indeed form early at ^{103}Sn, the measurement of $S_p(^{104}\mathrm{Sb})$ was necessary. In this context, I proposed to pursue these studies to determine its value by identifying and measuring the α-decay branch of ^{112}Cs, which is a well know proton emitter 47). The results of the experiment, carried out at the RMS of the HRIBF, allowed to set lower limits on $Q_p(^{104}\mathrm{Sb})$ and $Q_p(^{108}\mathrm{I})$, hence to constrain the respective range of values, ruling out the formation of the *rp*-process at ^{103}Sn. My contribution to this project consisted in preparing the proposal for the experiment, in contributing to the preparation of the experimental set-up, supervising the analysis of the experimental data and the manuscript preparation 48).

In an independent mass-measurement experiment, the last of the uncertain input parameters for *rp*-process calculations, namely the proton separation energy of ^{106}Sb, was established experimentally, ruling out definitively the possibility of formation of the Sn−Sb−Te cycle, which simply dies out after reaching Sn−Sb isotopes 49).

Study of nuclear reactions of astrophysical interest. In the period 2006-2010, within the framework of a post-doctoral research associate at the Department of Physics of the University of Milan, Italy, I could pursue my interest in nuclear astrophysics from a different perspective. In particular, the experience gained in nuclear physics techniques at other laboratories could be used to study thermonuclear reactions of astrophysical interest measured at the relevant energies, i.e. at or close-to the respective Gamow peak. The context that allowed such studies was the LUNA collaboration (Laboratory for Underground Nuclear Astrophysics). Thanks to the suppression of cosmic rays granted by the underground laboratories of Gran Sasso, LUNA is a facility unique in the world for the measurement of nuclear reactions of great astrophysical interest at energies as low as the Gamow peak (from tens to hundreds of keV in the centre-of-mass, depending on the reaction and the stellar temperature considered), or close to it. The facility includes an electrostatic accelerator (Cockcroft-Walton) with maximum voltage 400 kV and a series of detector- (HPGe, BGO, silicon) and target-systems (windowless gas target or solid targets) to be used for the measurement of the direct (p,*) or (α,*) reactions. My contribution to the collaborative LUNA effort included:

- a feasibility study for new reactions to investigate at LUNA, i.e. rate estimates and laboratory tests of the experimental set-up, study of beam-induced background effects and optimisation of the materials to be used in the target chamber. Among these reactions the most important is certainly the ^{2}H(^{4}He,γ)^{6}Li, a key reaction to understand the production of lithium during the big-bang nucleosyn-

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[47] "Search for α decay of ^{112}Cs", proposal number RIB163 at HRIBF (ORNL), 2006.

[48] L. Cartegni, C. Mazzocchi, et al., Phys. Rev. C 85 (2012) 014312.

[49] V.-V. Elomaa et al., Phys. Rev. Lett. 102 (2009) 252501.

thesis, and hence understand the detected ^{6}Li/^{7}Li abundance ratio. The data existing in literature at low energies for the ^{2}H(^{4}He,γ)^{6}Li cross section are obtained with indirect methods and are not in agreement with the higher-energy data obtained with direct methods. A direct measurement at low energy was therefore called for. In order to reach astrophysically-relevant energies with a direct measurement, an underground measurement was performed, as the background overground would be overwhelming. The results ruled out the standard big-bang nucleosynthesis production as possible explanation for the reported ^{6}Li abundance and non-standard (astro)physical processes will have to be involved in order to explain the ^{6}Li/^{7}Li abundance ratio 50),51).

- The study of the CNO-cycle reaction ^{15}N(p,γ)^{16}O. It is relevant for oxygen production and for all the CNO sub-cycles, since it is the bridge reaction between the CN and NO sub-cycles and all the further cycles. The measurement was performed using a high efficiency BGO detector and solid ^{15}N-enriched targets: apart from preparation/setting up the experimental set-up and participating in the data taking phase, which spanned over several months, I was responsible for one of the two analysis of the data (the data were analysed independently by two groups using different algorithms), while co-supervising the master student (Valentina Capogrosso) who graduated on part of one of the two data analysis 52),53),54),55).

- Contribution to the writing of a Letter of Intents (LOI) for a new accelerator to be placed underground which can reach higher (∼3 MV) energies (LUNA-MV project). The LOI was submitted for funding, which was granted. This new accelerator, presently under purchase, together with the continuation of the scientific programme at the present facility, will allow for the cross sections measurement of CNO and CNO-exit reactions, which form the seeds for the slow (*s*-), *r*- and *rp*-processes. They are at the basis of the stellar nucleosynthesis and the measurement of the cross-sections at the relevant energies is extremely important to understand the abundance of the various elements.

Study of rare decay modes. The development of an Optical Time Projection Chamber (OTPC) 56) at the University of Warsaw almost a decade ago opened the pos-

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[50] M. Anders, ..., C. Mazzocchi, ..., Phys. Rev. Lett. 113 (2014) 042501

[51] D. Trezzi, ..., C. Mazzocchi, ..., to be submitted to Astroparticle Physics

[52] A. Caciolli, C. Mazzocchi, et al., Astronomy and Astrophysics 533 (2011) A66

[53] C. Mazzocchi for the LUNA Collaboration, Proceedings of the 12th Int. Conf. on Nuclear Reaction Mechanisms, Varenna, Italy, 2009, CERN-Proceedings-2010-001, p. 495.

[54] Chiara Mazzocchi for the LUNA Collaboration, Acta Phys. Pol. 42 (2011) 785.

[55] V. Capogrosso, "Measurement of the cross section for the reaction ^{15}N(p,γ)^{16}O at astrophysical energies", Master thesis, University of Milan, 2009 (*in italian*)

[56] M. Ćwiok et al., IEEE Trans. Nucl. Sci. 52 (2005) 1895.

sibility to investigate a broad range of rare decay modes with very high sensitivity. The detection of one decay event is indeed sufficient to unambiguously identify the decay mode and establish its branching ratio. In its present version, the OTPC detector is a Time Projection Chamber with amplification stage formed by a stack of Gas Electron Multiplier foils and optical readout consisting of a CCD camera and a photomultiplier tube (PMT). The images recorded by the CCD camera together with the time distribution of light collected in the PMT allow to reconstruct the trajectory of the decay products 56),57),58). Such an approach, when coupled to a fragment separator, is ideally suited to study the decay by (multi-) charged-particle emission of very exotic isotopes, like two-proton ($2p$) radioactivity or β-delayed multi-particle emission.

- The radioactive process of simultaneous emission of two protons from the ground state of an atomic nucleus is the most recently observed type of decay and thus the least known. It may occur in an even-Z nucleus in the vicinity of the proton drip line when, due to pairing interactions between protons, the nucleus is bound against single-proton emission, while it is unbound against the emission of two protons. When the Q-value for $2p$ decay (Q_{2p}) is large enough, the emission of two protons may win the competition with the β^+ transition and become the dominant radioactive decay mode of such a nucleus. Studying $2p$ decay can provide information on the mechanism of the process itself, in particular on its true three-body nature, and on nuclear structure for very exotic, drip-line isotopes, which could not be obtained with other methods. Predictions of Q_{2p} values yielded three best candidates for observation of this rare decay mode 59),60),61): ^{45}Fe, ^{48}Ni and ^{54}Zn. The first case for which $2p$ radioactivity was experimentally proven was ^{45}Fe in 2002 62),63). I was part of the collaboration that carried on one of the two discovery experiments and I am co-author of the respective publication 62). Not long afterwards, the second case, ^{54}Zn, was announced 64).

  The OTPC detector was originally designed to obtain the first unambiguous proof of the $2p$ decay of ^{45}Fe and to study the angular correlations between the protons 57). In 2011 it was used to provide the first, direct and unabiguous identification of the $2p$ decay of ^{48}Ni 65),58). I was involved in the preparation and conduction of the measurement.

  The same set-up was recently employed at the NSCL to search for the new isotope ^{59}Ge and study the decay of ^{60}Ge. Both isotopes were considered to be candidates

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[57] K. Miernik et al., Phys. Rev. Lett 99 (2007) 192501.

[58] M. Pomorski, ..., C. Mazzocchi, ..., Phys. Rev. C 90, 014311 (2014).

[59] B.A. Brown, Phys. Rev. C 43 (1991) R1513.

[60] W.E. Ormand, Phys. Rev. C 55 (1997) 2407.

[61] B.J. Cole, Phys. Rev. C 54 (1996) 1240.

[62] M. Pfützner, ..., C. Mazzocchi, ..., Eur. Phys. J. A 14 (2002) 279.

[63] J. Giovinazzo et al., Phys. Rev. Lett. 89 (2002) 102501.

[64] B. Blank et al., Phys. Rev. Lett. 94 (2005) 232501.

[65] M. Pomorski, ..., C. Mazzocchi, ..., Phys. Rev. C 83 (2011) 061303(R).

for $2p$ emission. Of the two isotopes, the latter was observed only in the discovery experiment 10 years ago, when 3 ions were identified at the A1900 spectrometer at the NSCL [66], while the latter had not been observed yet. The analysis of the data collected in the recent (2014) NSCL experiment, which will constitute part of Aleksandra Ciemny PhD thesis, led to the first identification of the new isotope ^{59}Ge, for which I coordinated the data analysis [67]. The remaining part of the data on the decay spectroscopy of these isotopes is under analysis.

- A characteristic feature of exotic nuclei at the proton drip-line is the large energy released in β decay. As a consequence, highly excited and unbound states in the daughter nucleus can be populated in the decay and the β decay can be followed by emission of protons. Since the first observation of delayed proton emission almost 50 years ago, followed by the discovery of β-delayed two-proton emission in 1983, such decays have provided a wealth of information on structure of neutron-deficient nuclei far from stability, allowing tests of nuclear models and yielding data needed for the understanding of the astrophysical rp-process [68],[69].

  The first unambiguous observation of β-delayed three-proton emission (β3p) was successful only in 2007 when the OTPC was applied to study nuclei in vicinity of ^{45}Fe and β3p emission was identified in the β decays of ^{45}Fe [70] and ^{43}Cr [71]. A perfect candidate for observing this decay mode is ^{31}Ar. First claim of observation of this rare decay branch of ^{31}Ar was in 1992 [72], but could not be confirmed in a later measurement, which yielded only an upper limit for the branching ratio $b_{\beta 3p} < 0.11\%$ [73]. The non-identification for this decay mode was due to limited statistics and the non-optimal detection set-up, which was based on Si detectors. The OTPC detector provides an excellent tool to determine unambiguously this decay mode and its branching ratio with very few observed events. In an experiment at the GSI Fragment Separator ^{31}Ar ions were produced in the fragmentation of a ^{36}Ar beam, separated from the rest of the recoils generated and about 21000 of them were implanted inside the active volume of the OTPC detector, were they subsequently decayed. Here the ion and the decay products were observed [74],[75]. Unambiguous identification of 13 β3p events yielded

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[66] A. Stolz et al., Phys. Lett. B 627, 32 (2005).

[67] A.A. Ciemny,...,C. Mazzocchi,..., Phys. Rev. C 92 (2015) 014622.

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[69] M. Pfützner et al., Rev. Mod. Phys. 84 (2012) 567.

[70] K. Miernik et al., Phys. Rev. C 76 (2007) 041304(R).

[71] M. Pomorski et al., Phys. Rev. C 83 (2011) 014306.

[72] D. Bazin et al., Phys. Rev. C 45, 69 (1992).

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[74] M. Pfützner et al., GSI-SR2012-PHN-ENNA-EXP-17, GSI Report 2013-1 (2012).

[75] A.A Lis, C. Mazzocchi, ..., Phys. Rev. C 91 (2015) 064309

a branching ratio of (7±2)·10^{-4} 75),76), which is compatible within error bars with the Koldste *et al.* result 77). My involvement in this particular study consisted in preparing and optimising the detection set-up, coordinating and supervising the data analysis of the Master student (Aleksandra Ciemny (*nee* Lis)) working on the data 75),76).

Since 2010 I have been deeply involved in maintaining, upgrading and fully characterising the OTPC detector. This included, among others, proposing and running experiments to fully characterise the detector 78), measurements of the electron drift-velocy and a study of the light emission by the gas mixture used in the OTPC detector. The latter is needed in order to optimise the gas-mixture to be employed during experiment. The relevant measurements were performed by a Batchelor student (Aleksandra Ciemny (*nee* Lis)) under my direct supervision 79).

5.3 FUTURE PLANS, AN OUTLOOK

The research interest developed over my whole career have triggered new projects. In the mid-term time-range I plan to continue the study of rare decay-modes. The ground is being laid and experiments to look for β-delayed multi-particle emission from nuclei that have astrophysical interest (p- and rp-process nuclei) are being prepared for the cyclotron facility at Texas A&M, College Station TX, USA, and RIKEN, Tokyo, Japan. At the same time I am involved in projects to continue with the measurement of β-decay properties of very neutron-rich nuclei in the neighbourhood of ^{78}Ni. Experiments are already planned, e.g., at RIKEN and ISOLDE.

The experience gained on measurements with the OTPC detector and on measurements of thermonuclear reaction cross-section at stellar energies is being merged in a new project for which I am co-editor of the Technical Design Report for the physics program and detection set-up 80). Namely, this involves the development of a new TPC detector with innovative electronic read-out that will serve as an active target to measure cross-sections of astrophysical photo-disintegration reactions. This very ambitious project exploits the possibility to use the high-intensity monochromatic γ-ray beams that will be available at the new European Extreme Light Infrastructure facility at Magurele, Romania. Thermonuclear reactions, like the ^{12}C(α,γ)^{16}O, have cross sections that are too low to measure by means of the direct reaction even underground. By using the time-reversal principle, the cross section can be measured by studying the inverse (photo-disintegration) reaction. The scientific program includes

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[76] A.A. Ciemny, "Study of β decay of ^{31}Ar", Master thesis, University of Warsaw, 2015 (*in Polish*).

[77] G.T. Koldste et al., Phys. Rev. C 89 (2014) 064315

[78] "Characterisation of the Optical Time Projection Chamber (OTPC)", proposal number HIL051 at the Heavy Ion Laboratory, University of Warsaw, 2014.

[79] A.A. Lis, "*Study of light emission in the OTPC detector*", Batchelor thesis, University of Warsaw, 2013 (*in Polish*)

[80] RA4-TDR4 *"Charged Particle Detection at ELI-NP - Technical Design Report"*, April 2015.

also other important reactions that are at present not available for direct studies, among which are photo-disintegration of ^{21,22}Ne or ^{19}F. The project was positively evaluated by the International Scientific Advisory Board of the ELI-NP facility.

5.4 Service activity

Referee for Physics Letters B, European Physical Journal A, Acta Physica Polonica and Il Nuovo Cimento B.

5.5 Project coordination

After completion of the doctoral studies

- Research projects
  - Coordinator of the project ("*kierownik projektu*")) "Nuclear spectroscopy at the limits of stability", financed by the National Science Centre of the Polish Ministry of Science and Higher Education (OPUS9, contract number 2015/17/B/ST2/00581, 2016–).
  - Coordinator of the project ("*kierownik projektu*")) "Studies of β decay and nuclear structure in the neighbourhood of ^{78}Ni", financed by the National Science Centre of the Polish Ministry of Science and Higher Education (OPUS1, contract number 2011/01/B/ST2/02476, Dec. 2011 – Dec. 2014).
  - Co-Editor of the Technical Design Report "Charged Particles Detection at ELI-NP", April 2015.

- Didactic projects
  - Coordinator of the project "X-ray fluorescence analysis - laboratory experiment", financed by the Fund for Innovative Didactics, UW (FID2014) (continuation of the FID2012 project).
  - Coordinator of the project "X-ray fluorescence analysis - laboratory experiment", financed by the Fund for Innovative Didactics, UW (FID2012).

- International conferences organization
  - Editor of the proceedings "XXXII Mazurian Lakes Conference on Physics" published as Acta Phsyica Polonica B, vol. 43, 2012.
  - Editor of the proceedings "XXXIII Mazurian Lakes Conference on Physics" published as Acta Phsyica Polonica B, vol. 45, 2014.
  - Member of the organizing committee of the "XXXIII Mazurian Lakes Conference on Physics", Piaski, Poland, September 1-7, 2013.
  - Scientific secretary of the "XXXIV Mazurian Lakes Conference on Physics", Piaski, Poland, September 6-13, 2015.

- Spokesperson of the following experiments approved by the respective Program Advisory committees:
  - "Characterisation of the Optical Time Projection Chamber (OTPC)", proposal number HIL051 at the Heavy Ion Laboratory, University of Warsaw, 2014.
  - "Measurement of beta-delayed neutron properties of fission fragments", proposal number 3-01-584 at ILL Grenoble, 2011;
  - "Beta-delayed neutron properties of fission fragments", proposal number 3-01-594 at ILL Grenoble, 2011;
  - "Identification of excited states in ^{75}Ni", proposal number E10027 at NSCL (MSU), 2010;
  - "Search for α decay of ^{112}Cs", proposal number RIB163 at HRIBF (ORNL), 2006;
  - "Beta-decay studies of very neutron rich Fe and Mn isotopes", proposal number E06030 at NSCL (MSU), 2006;
  - "Decay spectroscopy of accelerated beam components: A test of the sensitivity of the ranging-out technique - Half-life measurement of ^{86,87}Ge", proposal number RIB128 at HRIBF (ORNL), 2004;

- Co-spokesperson of the following experiments approved by the respective Program Advisory committees:
  - "Neutron single-particle states and beta-delayed neutron branching ratios near ^{78}Ni", proposal number E05020 at NSCL (MSU), 2005;
  - "Alpha decay studies beyond ^{100}Sn", proposal number U202 at GSI-ISOL, 2002 (before completion of the doctoral studies).

- Local coordinator for
  - GSI-FRS experiment "Proton decay studies of heavy nuclei produced by projectile fragmentation reaction", proposal number S235.
  - "Identification of the decay of the T_Z=+1/2 nucleus ^{113}Ba", proposal number RIB045 at HRIBF (ORNL);

BEFORE AND AFTER COMPLETION OF THE DOCTORAL STUDIES

- Co-proposer of several experiements approved by the respective Program Advisory committees at the laboratories: GSI-Darmstadt, Germany; HRIBF-ORNL, USA; NSCL, USA; ILL-Grenoble, France; CERN-ISOLDE, Switzerland; LNL-Legnaro, Italy; LNS-Catania, Italy; LNGS-L'Aquila, Italy; TRIUMF-Vancouver, Canada; JAEA-Tokai, Japan; RIKEN, Japan.

5.6 LIST OF PRESENTATIONS

5.6.1 ORAL PRESENTATIONS: INVITED TALKS

AFTER COMPLETION OF THE DOCTORAL STUDIES

1. "*Nuclear reactions at astrophysical energies with gamma-ray beams: a novel experimental approach*", invited talk at the 5^{th} International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX5), Cracow, Poland, September 2015.
2. "*Beta-decay studies near* ^{78}Ni *at the HRIBF*", invited talk at the XXXIII Mazurian Lakes Conference, Piaski, Poland, September 2013.
3. "*Beta Decay of Most Neutron-Rich Ge and As Isotopes Discovered at LeRIBSS*", invited talk at the 5^{th} International Conference on Fission and Properties of Neutron-Rich Nuclei', Sanibel Island (FL), USA, November 2012.
4. "*Nuclear astrophysics deep underground: the LUNA experiment*", invited talk at the XLVIII International Winter Meeting on Nuclear Physics, Bormio, Italy, January 2010.
5. "*Alpha and proton decay above* ^{100}Sn", invited talk at the Fifth International Conference on Exotic Nuclei and Atomic Masses ENAM'08, Ryn, Poland, September 2008.
6. "*On the alpha decay of* ^{109}I *and its implications for the proton decay of* ^{105}Sb", invited talk at the Int. Conf. on Proton Emitting Nuclei and Related Topics, Lisbon, Portugal, June 2007.
7. "*Alpha decay studies in the* ^{100}Sn *region*", invited talk at the ECT* Workshop "Experiment–Theory Intersections in Modern Nuclear Structure", Trento, Italy, April 2007.
8. "*Beta-decay near the double shell closure at* ^{78}Ni", invited talk at the HRIBF Workshop - Nuclear Measurements for Astrophysics, Oak Ridge-TN, USA, October 2006.
9. "*Doubly magic character of* ^{78}Ni *– complex studies of simple nuclei*", invited talk at the American Physical Society (APS) Spring Meeting, Tampa-FL, USA, April 2005.

BEFORE COMPLETION OF THE DOCTORAL STUDIES OR ON THE DOCTORAL THESIS TOPIC

10. "*Decay of* ^{114}*Ba*",
invited talk at the Int. Symposium on Proton Emitting Nuclei PROCON2003, Legnaro, Italy, February 2003.

5.6.2 ORAL PRESENTATIONS: CONTRIBUTED TALKS

AFTER COMPLETION OF THE DOCTORAL STUDIES

1. "*Beta-decay of the most neutron-rich isotopes close to* ^{78}*Ni*",
talk at the 49th Zakopane Conference on Nuclear Physics, Zakopane, Poland, September 2014

2. "*An active time-projection chamber to study nuclear reactions of astrophysical interest*",
talk at the Workshop "Towards TDR of experiments with brilliant gamma-ray beams at ELI-NP", Magurele, Romania, June 2013.

3. "*Precision half-life measurement of* ^{7}*Be implanted in different materials*",
talk at the XXXII Mazurian Lakes Conference on Physics, Piaski, Poland, September 2011.

4. "*Nuclear astrophysics deep underground: the LUNA experiment*",
talk at the 45th Zakopane Conference of Nuclear Physics, Zakopane, Poland, September 2010.

5. "*Nuclear structure decay studies at and beyond* ^{78}*Ni*",
talk at the HRIBF, Upgrade for the FRIB Era: an HRIBF Users Workshop, Oak Ridge-TN, USA, November 2009.

6. "*Nuclear astrophysics deep underground: the case of the* $^{15}N(p,\gamma)^{16}O$ *reaction at LUNA*", talk at the 12th Int. Conf. on Nuclear Reaction Mechanisms, Varenna, Italy, June 2009.

7. "*Alpha decay of* ^{109}*I and the implications for the rapid-proton capture process*",
talk at the 10th Symposium on Nuclei in the Cosmos, Mackinac Island, MI, USA, July 2008.

8. "*Discovery of the alpha decay of* ^{109}*I*",
talk at the 2006 Division of Nuclear Physics (DNP) Annual Meeting, Nashville-TN, USA, October 2006.

9. “*On the alpha decay of* ^{109}I”,
talk at the Int. Conf. on Nuclei at the Limits, Nuclear Structure ’06, Oak Ridge TN, USA, July 2006.

10. “*Isomer and beta-decay studies of nuclei near* ^{78}Ni”,
talk at the 71st Annual Meeting of the Southeastern Section of the APS (SESAPS), Oak Ridge-TN, USA, November 2004.

11. “*Beta-delayed* γ *and neutron emission near the double shell closure at* ^{78}Ni”,
talk at the Int. Conference ENAM04, Pine Mountain-GA, USA, September 2004.

12. ”*Isomer and* β*-decay studies of nuclei near* ^{78}Ni”,
talk at the Int. Conference Nuclei at the Limits, Argonne National Laboratory, Argonne, USA, July 2004.

13. “*Isomer and beta-decay studies near* ^{78}Ni”,
talk at the APS Spring Meeting, Denver-CO, USA, May 2004.

Before completion of the doctoral studies or on the doctoral thesis topic

14. “*Alpha decay of* ^{114}Ba”,
talk at the Int. Symposium on Nuclear Clusters, Rauischholzhausen, Germany, August 2002.

15. “*Alpha decay of* ^{114}Ba”,
talk at the Spring Meeting of the German Physical Society (Deutsche Physikalische Gemeinschaft -DPG), Münster, Germany, March 2002.

16. “*Decay studies at the proton drip-line:* ^{60}Ga *and* ^{114}Ba”,
talk at the Int. Workshop on Exotic Nuclei at the Proton Drip-line, Camerino, Italy, September 2001.

17. “*Decay properties of* $N{\sim}Z$ *nuclei below* ^{100}Sn”,
talk at the Int. Workshop PINGST2000, Lund, Sweden, June 2000.

5.6.3 Oral presentations: seminars

After completion of the doctoral studies

1. “*Nuclear reactions at astrophysical energies with gamma-ray beams*”,
invited seminar at the Institute of Nuclear Physics, PAN, Cracow, March 2015.

2. "*Effect of external conditions on the half-life of* ^{7}Be ",
   invited seminar at the Department of Physics, Nuclear Physics group, University of Tennessee, Knoxville-TN, USA, February 2013.

3. "*Beta-delayed neutron decay in the vicinity of* ^{78}Ni",
   invited seminar at Institut Leu Langevin, Grenoble, France, February 2011.

4. "*Nuclear astrophysics deep underground: the LUNA experiment*",
   invited seminar at the Department of Physics, Nuclear Physics group, University of Tennessee, Knoxville-TN, USA, August 2009.

5. "*Astrofisica nucleare in laboratori sotterranei: l'esperimento luna*",
   invited seminar at Laboratori Nazionali del Sud, Catania, Italy, July 2009.

6. "*Nuclear structure measurements for astrophysics: from the Earth surface to underground laboratories*",
   invited seminar at the Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland, May 2007.

7. "*Doubly magic character of* ^{78}Ni *– complex studies of simple nuclei*",
   invited seminar at the Department of Physics, University of Milan, Milan, Italy, November 2005.

8. "*Recent measurements at the GSI On-line Mass Separator*",
   invited seminar at the Nuclear Spectroscopy Division, Warsaw University, Warsaw, Poland, November 2002.

9. "*Doubly magic character of* ^{78}Ni *– complex studies of simple nuclei*",
   seminar at the Physics Division, Oak Ridge National Laboratory, Oak Ridge-TN, USA, February 2005.

10. "*Doubly magic character of* ^{78}Ni *– complex studies of simple nuclei*",
    seminar at the Department of Physics, Nuclear Physics group, University of Tennessee, Knoxville-TN, USA, February 2005.

BEFORE COMPLETION OF THE DOCTORAL STUDIES OR ON THE DOCTORAL THESIS TOPIC

11. "*Decay studies near the proton drip-line*",
    seminar at the Department of Physics, Nuclear Physics group, University of Tennessee, Knoxville-TN, USA, October 2003.

12. "*Decay studies of nuclei near the proton drip-line*",
    seminar at the Department of Physics, EXAKT group, of Mainz University, Mainz, Germany, April 2002.

13. "*Decay studies of nuclei near the proton-drip line: the cases of* ^{50}*Ni,* ^{60}*Ga and* ^{114}*Ba*",
seminar at the Division of Nuclear Physics II, GSI-Darmstadt, Germany, March 2002.

5.6.4 ORAL PRESENTATIONS: OTHER PRESENTATIONS

AFTER COMPLETION OF THE DOCTORAL STUDIES

1. "*Characterisation of the Optical Time Projection Chamber (OTPC)*",
Program Advisory Committee meeting of the Heavy Ion Laboratory, University of Warsaw: presentation of the proposal for a test experiment, November 2014.

2. "*Alpha decay studies near* ^{100}*Sn at the HRIBF*",
Joint ATLAS-HRIBF-NSCL-FRIB User Workshop, presentation on behalf of the UT/ ORNL/ UNIRIB/ ORAU/ Milan/ Liverpool/ Vanderbilt/ Warsaw/ KU Leuven/ Oslo/ Padua/ Naples/ NSCL/ Maryland/ Mississippi State Univ./ East Tenn. State Univ./ JIHIR/ Cracow collaboration, August 2011

3. "*Preliminary results on spectroscopy of extremely neutron rich nickel isotopes*",
NSCL User Workshop, presentation of the results from experiment E05020 on behalf of the UT/ NSCL/ Milan/ ORNL/ UNIRIB/ Warsaw/ Cracow/ Mississippi State Univ. collaboration, August 2007.

4. Meeting of the collaboration UNIRIB , Oak Ridge (TN), USA, January 2006:
    - "*Report from two RMS measurements (RIB045) Identification of the decay of* T_Z*=+1/2 nucleus* ^{113}*Ba*", on behalf of the collaboration UT/ ORNL/ JIHIR/ UNIRIB/ Warsaw/ Cracow/ Mississippi State/ Vanderbilt/ Maryland;
    - "*Accepted proposal for an experiment at the HRIBF (RIB-128) Decay spectroscopy of accelerated beam components: a test of the sensitivity of the ranging-out technique. Half-life measurements of* ^{86,87}*Ge*", on behalf of the collaboration UT/ ORNL/ Mississippi State/ LSU/ Warsaw/ Vanderbilt.

5. "*Decay Spectroscopy Studies at the HRIBF Recoil Mass Spectrometer in 2005*",
HRIBF-PAC12, presentation on behalf of the HRIBF Decay Spectroscopy Group, December 2005.

6. "*Beta delayed gamma and neutron emission near the double shell closure at* ^{78}*Ni*",
student presentation at the Fourth RIA Summer School on Exotic Beam Physics, Berkeley (CA), USA, August 2005.

7. Meeting of the collaboration UNIRIB, Oak Ridge (TN), USA, November 2004:

- “*Accepted proposal for an RMS experiment Identification of the decay of Tz=+1/2 nucleus* ^{113}*Ba*”, on behalf of the collaboration UT/ ORNL/ LSU;
- “*Accepted proposal for an experiment at the HRIBF (RIB-128) Decay spectroscopy of accelerated beam components: a test of the sensitivity of the ranging-out technique. Half-life measurements of* ^{86,87}*Ge*”, on behalf of the collaboration UT/ ORNL/ MississippiState/ LSU/ Warsaw/ Vanderbilt.

8. “*Beta-delayed neutron and* γ*-rays from neutron-rich cobalt isotopes*”,
NSCL User Workshop, presentation of the results from experiment E01027 on behalf of the UT/ NSCL/ ORNL/ UNIRIB/ Warsaw/ Vanderbilt/ JIHIR/ Mississippi State Univ. collaboration, October 2004.

9. “*Test of production rates and background for* ^{45}*Fe*”,
NSCL User Workshop, presentation of the results from the test experiment E03513 on behalf of the NSCL/ Warsaw/ CEN-Bordeaux/ UT/ ORNL collaboration, October 2004.

10. Meeting of the collaboration UNIRIB, Oak Ridge (TN), USA March 2004:
    - “*Identification of the decay of* T_Z*=+1/2 nucleus* ^{113}*Ba*”, on behalf of the collaboration UT/ ORNL/ LSU.

BEFORE COMPLETION OF THE DOCTORAL STUDIES

11. “*Alpha decay studies beyond* ^{100}*Sn*”,
GSI-PAC, presentation of the proposal U202 for an experiment at the GSI-ISOL facility, June 2002.

12. Meeting of the collaboration Warsaw-GSI-Valencia, Warsaw, Poland, April 2002:
    - “*Remeasurement of the alpha decay chain* $^{114}Ba \rightarrow {}^{110}Xe \rightarrow {}^{106}Te \rightarrow {}^{102}Sn$”;
    - “*Decay Study of* ^{50}*Ni at the FRS*”;
    - “*Proton decay studies of heavy nuclei produced by projectile fragmentation reactions*”.

13. “*Report from S202 and outlook on S235*”,
GSI-FRS User Workshop, presentation on behalf of the collaborations from experiments S202 -Warsaw/ Bordeaux/ GSI/ Edinburgh/ UT/ ORNL/ GANIL/ Liverpool- and S235 -GSI/ Warsaw/ Edinburgh/ ORNL/ Argonne, February 2002.

5.6.5 Poster presentations

After completion of the doctoral studies.

1. “*Nuclear reactions at astrophysical energies with gamma-ray beams: a novel experimental approach*”,
poster at the XXXIV Mazurian Lakes Conference on Physics, Piaski, Poland, September 2015.

2. “*On the alpha decay of* ^{109}I”,
oral poster at the Int. Conf. on Nuclei at the Limits, Nuclear Structure '06, Oak Ridge (TN), USA, July 2006.

3. “*Beta-delayed* γ *and neutron emission near the double shell closure at* ^{78}Ni”,
oral poster at the Int. Conference ENAM04, Pine Mountain (GA), USA, September 2004.

Before completion of the doctoral studies or on the doctoral thesis topic

4. “*First measurement of* β*-decay properties of the proton drip-line nucleus* ^{60}Ga”,
poster at the DPG Spring Meeting, Münster, Germany, March 2002.

5. “*Alpha decay of* ^{114}Ba”,
poster at the Int. Conf. ENAM2001, Hämeenlinna, Finland, July 2001.

Warsaw, January 26th, 2016

Chiara Mazzocchi