Beta Decay Studies of Proton Rich Nuclei, an Important Ingredient for rp-Process Calculations

B. Rubio, L. Kucuk, A. Orrigo, Y. Fujita, W. Gelletly, Bertram Blank, T. Adachi, P. Aguilera, J. Agramunt, A. Algora, et al.

Proc. 14th Int. Symp. on Nuclei in the Cosmos (NIC2016)
JPS Conf. Proc. **14**, 010510 (2017)
https://doi.org/10.7566/JPSCP.14.010510

Beta Decay Studies of Proton Rich Nuclei, an important ingredient for rp-process calculations.

B. Rubio[1], L. Kucuk[2], S.E. A. Orrigo[1], Y. Fujita[3 4], W. Gelletly[5], B. Blank[6], T. Adachi[4], P. Aguilera[1,7] J. Agramunt[1], A. Algora[1], P. Ascher[6], B. Bilgier[2], L. Cáceres[8], R. B. Cakirli[2], G. de France[8], F. de Oliveira Santos[8], H. Fujita[4], E. Ganioğlu[2], M. Gerbaux[6], J. Giovinazzo[6], S. Grévy[6], O. Kamalou[8], H. C. Kozer[2], T. Kurtukian-Nieto[6], M. Marqués[9], F. Molina[1 7], D. Nishimura[10] H. Oikawa[10] Y. Oktem[2], L. Perrot[9], L. Popescu[11], R. Raabe[8], A. M. Rogers[12], P. C. Srivastava[8], G. Susoy[2], C. Stodel[8], T. Suzuki[4], A. Tamii[4], J. C. Thomas[8],

[1]*IFIC (CSIC-Univ. Valencia), E 46071 Valencia, Spain*
[2]*Department of Physics, Istanbul University, Istanbul, 34134, Turkey*
[3]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[4]*RCNP, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[5]*Department of Physics, University of Surrey, Guildford GU2 7XH, Surrey, UK*
[6]*CENBG, CNRS/IN2P3 - Université de Bordeaux, 33175 Gradignan Cedex, France*
[7]*CCHEN, Casilla 188-D, Santiago, Chile*
[8]*GANIL, CEA/DSM - CNRS/IN2P3, BP 55027, F-14076 Caen, Cedex 5, France*
[9]*LPC, F-14050 Caen, France*
[10]*Department of Physics, Tokyo University of Sciences, Noda, Chiba 278-8510, Japan*
[11]*SCK.CEN, Boeretang 200, 2400 Mol, Belgium*
[12]*ANL, Argonne, Illinois 60439, USA*

E-mail: berta.rubio@ific.uv.es

(Received Received September 16, 2016)

We have performed a series of beta-decay experiments at fragmentation facilities on T_z=-1/2, T_z=-1 and T_z=-2 nuclei. Most of these nuclei lie on the rp-process path and therefore some of the quantities we have measured such as $T_{1/2}$ values are important ingredients in performing reaction flow calculations for light curve estimates and testing astrophysical models of X-ray bursters. At this conference we have presented the results of measurements of $T_{1/2}$ values for 25 nuclei and compared with previous values.

KEYWORDS: rp-process, beta decay experiments, fragmentation facilities.

1. Introduction, experiments and results

Many of the heavier neutron-deficient nuclei are thought to be produced in the astrophysical rp-process. The site of the rp-process is thought to be on the surfaces of neutron stars where H and He from a companion star are accreting. It occurs during the repeated thermonuclear flashes, called X-ray bursts. There have been many attempts to model X-ray bursters, partly because it might help us to understand the properties of neutron stars. To test such astrophysical models requires a solid and reliable foundation of measurements of the properties of nuclear reactions and decays along the rp-process pathway. Among these properties the decay half-lives are important.

Here we present a brief summary of the results we have obtained at different fragmentation facilities, namely GSI-Darmstadt, GANIL-Caen, RIKEN-Nishina Center-Tokyo on the beta decay of proton rich nuclei. A summary of the nuclei analysed so far are presented in Tables I-V.

The first experiment was performed at GSI, as part of the Stopped-beam RISING campaign. The

Table I. $T_{1/2}$ values for T_z = -1 nuclei measured at GSI (see text). Ref. [3].

Parent Nucleus	Number of Implanted Ions	$T_{1/2}$ (ms) Literature	$T_{1/2}$[ms] Present Work
^{54}Ni	6.38 10^6	111(7) [11] 113(9) [12]	114.2(3)
^{50}Fe	2.80 10^6	155(11) [13]	152.1(6)
^{46}Cr	3.30 10^6	240(140) [14]	224.3(13)
^{42}Ti	6.46 10^5	208.14(45) [15]	211.7(19)

Table II. $T_{1/2}$ values for T_z = -1/2 nuclei measured at GANIL in 2008 (see text).

Parent Nucleus	Number of Implanted Ions	$T_{1/2}$(ms) Literature	$T_{1/2}$(ms) Present Work
^{63}Ge	2.40 10^4	150(9) [16] 95(22) [17]	156(11)
^{61}Ga	1.35 10^5	148(19) [16] 150(30) [17] 168(3) [18]	163(5)
^{59}Zn	1.19 10^6	173(14) [16] 182.0(18) [19]	174(2)
^{57}Cu	5.49 10^5	183(17) [16] 196.3(7) [20]	195(4)
^{55}Ni	2.70 10^6	196(5) [16] 204(3) [21] 209(5) [22]	203(2)
^{53}Co	1.71 10^6	240(20) [21] 240(9) [23]	245(3)
^{51}Fe	7.85 10^5	305(5) [23] 310(5) [22]	288(6)
^{49}Mn	9.25 10^4	382(7) [23] 384(17) [24]	380(30)
^{47}Cr	1.52 10^4	508(10) [25] 472(8) [26]	460(80)

nuclei ^{54}Ni, ^{50}Fe, ^{46}Cr and ^{42}Ti were produced by the fragmentation of a ^{58}Ni beam at 680 MeV per nucleon on a 400 mg/cm^2 Be target in separate runs optimised to transport and implant the nucleus of interest. The SIS-18 synchrotron [1] delivered the ^{58}Ni primary beam with a spill structure of 10 s ON and 3 s OFF and an average intensity of 2×10^9 particles per spill. The ions were selected by the FRS [2] and then implanted in one DSSSD of an array of six, each with 16 X and 16 Y strips and thickness of 1 mm. The implanted ions and the β-particles emitted subsequently were detected in the DSSSDs. β-delayed gamma rays were detected in an arrays of 15 Ge CLUSTER detectors [3].

Two subsequent experiments were carried out at the GANIL-LISE3 fragmentation facility [4]. The first experiment in 2008 at GANIL involved the projectile fragmentation of a primary beam of $^{64}Zn^{29+}$, with an energy of 79 MeV per nucleon and an average intensity of 17 pnA, on a natural Ni target with a thickness of 236 mg/cm^2. A range of proton-rich nuclei was produced and the fragments were selected by the LISE3 separator and implanted in a single DSSSD with a thickness of 1.004 mm.

Table III. $T_{1/2}$ values for T_z = -1 nuclei measured at GANIL in 2008 (see text).

Parent Nucleus	Number of Implanted Ions	$T_{1/2}$(ms) Literature	$T_{1/2}$(ms) Present Work
^{62}Ge	6.08 10^3	129(35) [16]	76(6)
^{60}Ga	4.96 10^4	70(13) [16] 70(15) [27]	76(3)
^{58}Zn	1.77 10^5	86(18) [28] 83(10) [16]	86(2)
^{56}Cu	1.77 10^5	82(9) [16] 95(3) [29]	80(2)
^{54}Ni	2.41 10^5	103(9) [16] 106(12) [21] 114.2 (3) [3]	110(2)
^{52}Co	8.24 10^4	115(23) [30]	111(4)
^{50}Fe	1.35 10^4	155(11) [13] 152.1(6) [3]	145(13)

Table IV. $T_{1/2}$ values for T_z = -2 nuclei measured at GANIL in 2010 (see text). Ref. [5,6].

Parent Nucleus	Number of Implanted Ions	$T_{1/2}$(ms) Literature	$T_{1/2}$(ms) Present Work
^{48}Fe	4.98 10^4	45.3(6) [31] 44(7) [32]	51(3)
^{52}Ni	5.32 10^5	40.8(2) [31] 38(5) [33]	42.8(3)
^{56}Zn	8.86 10^3	30.0(17) [31]	32.9(8)

The second experiment at GANIL was carried out in 2010. This time it involved the fragmentation of a $^{58}Ni^{26+}$ primary beam, with an energy of 74.5 MeV per nucleon and an average intensity of 140 pnA, on a natural Ni target of 120 mg/cm^2. The fragments were again selected in LISE3 and, this time, they were implanted in a DSSSD with a thickness of 300 μm which was also used to detect the β-delayed protons [5,6]. In both cases, β-delayed γ-rays were detected with four CLOVER detectors.

A fourth experiment was carried out at the RIKEN Nishina Center in 2015 as part of an experimental campaign based on the projectile fragmentation of a fully-stripped primary beam of ^{78}Kr, with an energy of 345 MeV per nucleon and an intensity $\leq$ 300 pnA, on Be targets of thickness 5 or 7 mm. The fragments were separated in flight by the BigRIPS separator [8] and implanted in three, 1 mm thick DSSSDs of the WAS3ABi array [9] at the end of the Zero degree spectrometer. In this case the DSSSDs had 40 X and 60 Y strips. They were surrounded by the EURICA γ-array [34].

Table V. $T_{1/2}$ values for T_z = -2 nuclei measured at GANIL in 2010 (see text). Ref. [7].

Parent Nucleus	$T_{1/2}$(ms) Literature	$T_{1/2}$(ms) Present Work	Parent Nucleus	$T_{1/2}$(ms) Literature	$T_{1/2}$(ms) Present Work
$^{52}Co^{2+}$	-	102(6)	$^{52}Co^{6+}$	115(23) [30]	112(3)

In all cases the analysis followed similar general pattern, [3] and [6]. The nucleus, whose β-decay was of interest, was selected by setting gates off-line on the ΔE-time of flight matrix. Then all of the correlations in time between the implants and the decay events were constructed. The correlation time T_{corr} is defined as the time difference between a decay event in a given pixel of the DSSSD and any implantation signal that occurred before or after it in the same pixel that satisfied the conditions required for the identified nuclear species. This procedure means that all true correlations are observed but at the expense of a large number of random correlations. The analysis of such spectra has been described in detail in [3] and [6]. The spectra are fitted to the combination of the background plus all of the decay modes involved, according to the Bateman equations, in each particular case.

The results obtained for the four experiments are shown separately in tables I-V. In the case of the experiment at RIKEN, many nuclei were produced and studied, see for instance [10]. Preliminary results for the analysis of the $T_{1/2}$-values of the T_z=-1 nuclei ^{58}Zn and ^{66}Se and for the T_z=-2 nucleus ^{64}Se, are reported in ref. [35]. Many others will follow in due course.

References

[1] M. Steiner et al., Nucl. Instrum. Methods Phys. Res A **312**, 420 (1992)
[2] H. Geissel at al., Nucl. Instrum. Methods Phys. Res B **70**, 286 (1992)
[3] F. Molina et al., Phys. Rev. C **91**, 014301 (2015)
[4] R. Anne and A. C. Mueller, Nucl. Instrum. Methods Phys. Res B **70**, 276 (1992)
[5] S. E. A. Orrigo et al., Phys. Rev. Lett **112**, 222501 (2014)
[6] S. E. A. Orrigo et al., Phys. Rev. C **93**, 044336 (2016)
[7] S. E. A. Orrigo at al., arXiv:1605.08769 [nucl-ex], in print Phys. Rev. C.
[8] T. Kubo et al., Prog. Theor. Exp. Phys. **2012**, 03C003 (2012)
[9] S. Nishimura et al., RIKEN Accl. Progr. Rep. **46**, 182 (2013)
[10] B. Blank et al., Phys. Rev. C **93**, 061301 (R) (2016)
[11] I. Reusen et al., Phys. Rev. C **59**, 2416 (1999).
[12] J. Su et al., Phys. Rev. C **87**, 024312 (2013).
[13] V. T. Koslowsky et al., Nucl. Phys. A **624**, 293 (1997).
[14] T. K. Onishi et al., Phys. Rev. C **72**, 024308 (2005).
[15] T. Kurtukian Nieto et al., Phys. Rev. C **80**, 035502 (2009).
[16] M. J. López Jiménez et al., Phys. Rev. C **66**, 025803 (2002)
[17] J. A. Winger et al., Phys. Rev. C **48**, 3097 (1999)
[18] L. Wiessman et al., Phys. Rev. C **65**, 044321 (2002)
[19] Y. Arai et al., Nucl. Phys. A **420**, 193 (1984)
[20] D. R. Semon et al., Phys. Rev. C **53**, 96 (1996)
[21] I. Reusen et al., Phys. Rev. C **59**, 2416 (1999)
[22] J. Aysto et al., Phys. Lett. B **138**, 369 (1984)
[23] J. Honkanen et al., Nucl. Phys. A **496**, 462 (1989)
[24] J. C Hardy et al., Phys. Lett. B **91**, 207 (1980)
[25] T. W. Brows et al., Phys. Rev. C **31**, 1490 (1985)
[26] A. R. Farhan et al., Nucl. Phys. A **597**, 387 (1996)
[27] E. Roeckl et al., Proceedings of the ISOL 01 Conference, Oak Ridge, CA (2011)
[28] A. Jokinen et al., Eur. Phys. J. A **3**, 271 (1998)
[29] R. Borcea et al., Nucl. Phys. A **695**, 69 (2001)
[30] E. Hagberg et al., Nucl. Phys. A **613**, 183 (1997)
[31] C. Dossat et al., Nucl. Phys. A **792**, 18 (2007)
[32] L. Faux et al., Nucl. Phys. A **602**, 167 (1996)
[33] L. Faux et al., Phys. Rev. C **49**, 2440 (1994)
[34] P. A. Söderström et al., Nucl. Instrum. Methods Phys. Res B **317**, 649652 (2013)
[35] B. Rubio et al. RIKEN Accl. Progr. Rep. **49**, (2016)