Fine structure in one-proton emission studied at Oak Ridge

K. P. Rykaczewski[1], R. Grzywacz[1,2], J. C. Batchelder[3], C. R. Bingham[1,4], D. Fong[5], T.N. Ginter[1,5,6], C. J. Gross[1], J. H. Hamilton[5], D. J. Hartley[4], J. K. Hwang[5], Z. Janas[2,7], M. Karny[2,7], W. Królas[5,7,8] W.D. Kulp[9], Y. Larochelle[4], T. A. Lewis[1], K. H. Maier[1,7], J. W. McConnell[1], A. Piechaczek[10], A. V. Ramayya[5], K. Rykaczewski[11], D. Shapira[1], M. N. Tantawy[4], J. A. Winger[12], C. -H. Yu[1], E. F. Zganjar[10], K. Hagino[13], A. T. Kruppa[6,14], W. Nazarewicz[1,4,15], P. Semmes[16] and T. Vertse[6,14]

[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[2]*Institute of Experimental Physics, Warsaw University, PL 00-681 Warsaw, Poland*
[3]*UNIRIB Oak Ridge Associated Universities, Oak Ridge, TN 37831, USA*
[4]*Dept. of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*
[5]*Dept. of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA*
[6]*NSCL, Michigan State University, East Lansing, MI 48824, USA*
[7]*Joint Institute for Heavy Ion Research, Oak Ridge, TN 37831, USA*
[8]*H. Niewodniczański Institute of Nuclear Physics, PL 31-342 Kraków, Poland*
[9]*Dept. of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA*
[10]*Dept. of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA*
[11]*Oak Ridge High School, Oak Ridge, TN 37830, USA*
[12]*Dept. of Physics and Astronomy, Mississippi State University, Mississippi State, MS 39762, USA*
[13]*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[14]*Institute of Nuclear Research, Hungarian Academy of Sciences, H 4001 Debrecen, Hungary*
[15]*Institute of Theoretical Physics, Warsaw University, PL 00-681 Warszawa, Poland*
[16]*Dept. of Physics, Tennessee Technological University, Cookeville, TN 38505, USA*

Abstract. Two observations of fine structure in proton emission are reported : 3-μs ^{145}Tm and 4-ms ^{141}Ho. These experiments were performed using the Recoil Mass Separator (RMS) at the Holifield Radioactive Ion Beam Facility at Oak Ridge. The signals from the RMS detectors were digitally processed using Digital Gamma Finder modules. The fine structure branching ratios, 9.6±1.5% and 0.70±0.15%, and measured energies of the 2^+ excited levels in daughter nuclei, 330 and 202 keV, respectively, helped us to determine the deformations and wave functions of proton-emitting states.

There are over thirty proton-radioactive nuclei identified up to date, with about forty proton-emitting ground- and isomeric-states [1, 2, 3, 4]. However, fine structure in proton emission was observed only in few cases. A pioneering experiment on the decay of odd-Z even-N isotope ^{131}Eu was performed at the Fragment Mass Analyzer (FMA) at Argonne. Proton transitions to the 0^+ ground-state and to the 2^+ excited state in ^{130}Sm were observed [5].

The first observation of the fine structure in the proton emission from an odd-odd nucleus, ^{146gs,m}Tm, was made at the Recoil Mass Separator (RMS) at the Holifield Radioactive Ion Beam Facility (HRIBF) in Oak Ridge [6]. Reinvestigation of odd-odd

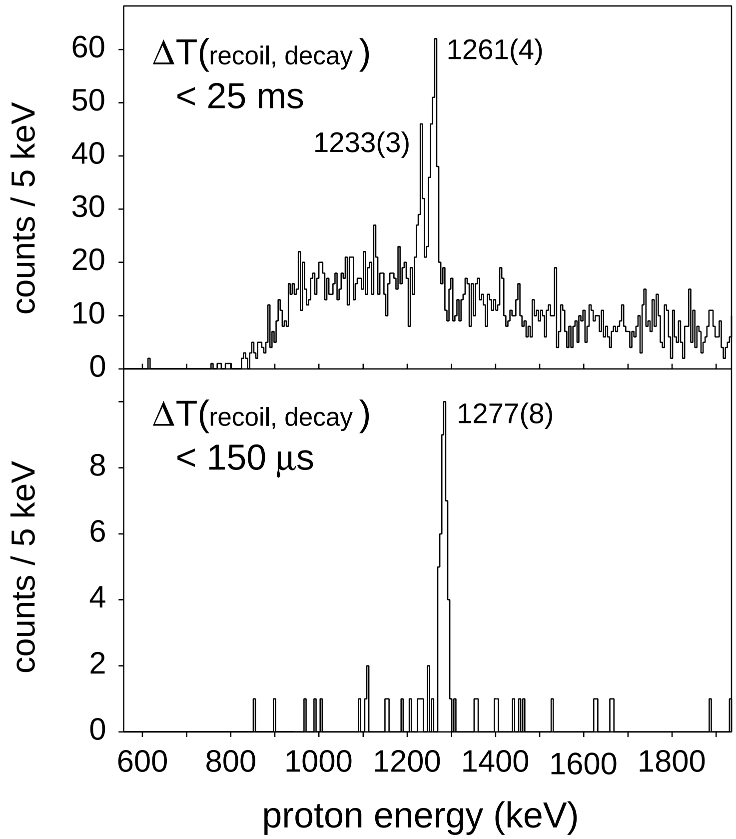

FIGURE 1. The energy spectra of proton events collected within 25 ms (upper panel) and 150 μs (lower panel) after an implantation of A=150 recoils into the DSSD. The recoiling nuclei were produced using a 292 MeV ^{58}Ni beam on a 0.54 mg/cm^2 ^{96}Ru target [6, 7]. The charge reset foil was placed 10 cm behind the target. It restores the charge state of a recoiling ion, changed after an isomeric deexcitation involving a conversion electron [8]. Observed increase in the yield of ^{150m}Lu proton events suggests the presence of such short-lived isomeric levels on the deexcitation path leading to ^{150m}Lu [6, 7]. Use of a converging solution for the RMS optics [8] resulted in the collection of ^{150}Lu ions in two charge states. The slits were set in a less restrictive way in comparison to the previous RMS study of ^{150}Lu [9]. A small fraction of neighboring activity ^{151gs}Lu (E_p=1233 keV) can be seen near the ^{150gs}Lu line (E_p=1261 keV) - upper panel. Better energy calibration and improved counting statistics yielded more accurate values for the energy (E_p=1277(8) keV) and half-life ($T_{1/2}$=39(+8,-6) μs) for proton emission from ^{150m}Lu. No evidence has been obtained for the fine structure in proton emission from ^{150m,gs}Lu. However, the peak-like weak structures, e.g., around 1.11 - 1.12 MeV, are worth further reinvestigation.

^{150gs,m}Lu decay did not offer a clear evidence for fine structure, see the spectra in Fig.1.

Here, we report the results of two experiments at the RMS. The decays of ^{145}Tm [10, 11] and of ^{141gs}Ho [12, 13, 14] were remeasured. In both RMS experiments, the proton transitions to the 0^+ ground-state and to the 2^+ excited state were found.

A description of the RMS and experimental techniques used for proton radioactivity studies are given in [8, 15, 16, 17]. Briefly, the radioactive nuclei are produced at the target using a beam accelerated by the 25 MV Tandem. Recoiling products of fusion-

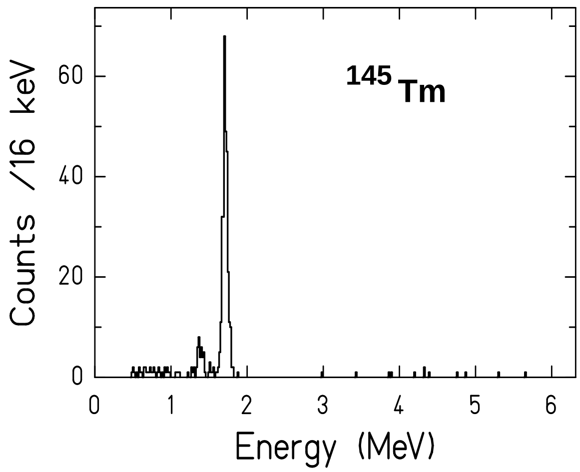

FIGURE 2. The energy spectrum of proton events collected within 0.5 to 10 μs after implantation of A=145 recoils into the DSSD. Similar halflives of 3.1(3) μs and 2.7(10) μs were obtained from the analysis of the decay pattern of 1.73 MeV and 1.40 MeV lines, respectively.

evaporation reactions are separated by magnetic and electric fields, according to their kinetic energy (acceptance $\pm$ 10%) and mass-over-charge Q/A value. Primary beam rejection is excellent and allows us to run with over 20 pnA beam intensity. For the beams of 5 MeV/u ^{54}Fe or ^{58}Ni impinging on a 1 mg/cm^2 ^{92}Mo target, almost no beam particles practically are reaching the detectors at the RMS final focus. The typical time of flight of fusion-evaporation products through the RMS is about 2.2 μs, and the mass separation is around 1:400. Before implantation, the recoils trigger a position-sensitive Microchannel Plate Detector (MCP) and can be slowed down by a degrader foil. The MCP [18] was designed to determine the position and intensity of radioactive ion beams at the HRIBF. However, this detector has nearly 100% efficiency for recoiling fusion products separated by the RMS. The recoiling ions in two neighboring charge states, e.g., ^{145}Tm^{+26} and ^{145}Tm^{+27}, can be implantated in the 40mm by 40 mm Double-sided Silicon Strip Detector (DSSD). The RMS transmission efficiency is about 5% for such converging ion optics.

The signals from MCP and DSSD detectors are digitally processed using Digital Gamma Finder (DGF4C) modules [19, 15, 16, 17]. The development of this novel pulse processing technique was critical for a search for weak proton transitions, in particular for the short-lived activity ^{145}Tm [11]. Two data acqusition modes can be selected for the DGF module. The 25-μs section of the preamplifier pulse around its rising edge can be recorded and analyzed further off-line. The digital image of the signal is obtained with 25 nanosecond sampling rate. To reduce the data stream, only the pulses with the implantation and decay signals overlapping within a 10 μs time interval are selected by the DGF on-board processors. This, so called “proton-catcher” mode was used during the ^{145}Tm study [11]. In a standard DGF operation mode, the energy and arrival time of the signal is derived on-board, using a trapezoidal filter algorithm. This operation mode is used to study longer-lived proton emitters like the 4-ms activity of ^{141gs}Ho.

The proton energy spectrum correlated with mass 145 recoils measured by the DSSD is shown in Fig. 2. It was derived from the analysis of DSSD preamplifier traces containing overlapping recoil and decay signals [11]. Two proton lines were observed in microsecond time correlations with mass A=145 recoils. The 1.73 MeV line was assigned earlier to the decay of ^{145}Tm [10]. The new line at 1.40 MeV has a similar halflife, of about 3 μs, suggesting the assignment to the activity of ^{145}Tm. Since the daughter activity is an even-even nucleus ^{144}Er, the interpretation of the 1.73 MeV and 1.40 MeV proton lines as the transitions populating the 0^+ ground-state ($I_p(0^+)$ of 90%) and the 2^+ excited state ($I_p(2^+)$=9.6(15)%) is obvious. The derived energy of 0.33(1) MeV is close to the E(2^+) for ^{138}Sm, ^{140}Gd and ^{142}Dy, which are less exotic N=76 isotones. The valence correlation scheme N_pN_n [20] suggests similar E(2^+) for ^{144}Er and its "N=82 mirror" nucleus ^{156}Er. Indeed, 0.33(1) MeV is close to known energy of 0.343 MeV for the 2^+ state in ^{156}Er. Similarly good agreement with N_pN_n systematics was found after the observation of fine structure in proton emission from ^{131}Eu [5]. The derived 2^+ state energy of 121$\pm$7 keV was close to the predicted value of 120$\pm$20 keV [21]. However, sometimes the shapes and level energy spectra of even-even nuclei near the proton drip line may be more complex than is accounted by the valence correlation scheme. The E(2^+) value predicted as 160$\pm$20 keV [21] for ^{140}Dy was found to be 202.2 keV by the studies of ^{140m}Dy decay [22, 23]. Such energy difference, about 200 keV, was also found for two lines in the proton energy spectrum measured for ^{141gs}Ho activity at the RMS, see Fig. 3. It is a first observation of a very weak proton transition (I_p=0.70$\pm$0.15%) to the 2^+ excited state in ^{140}Dy, in addition to the dominating ground-state-to-ground-state decay.

This small I_p value is in agreement with an upper limit of $I_p(2^+)$=1% obtained from the FMA study of ^{141gs}Ho decay [24].

The measured values of 2^+ energies can be used to estimate the deformation of the even-even nuclei [25, 26]. Using recent energy level systematic analyzed by Raman *et al.* [26], one obtains the deformation parameters of β_2=0.18 for ^{144}Er and β_2 about 0.23-0.24 for ^{140}Dy. The latter value is close to the estimation of β_2=0.25(4) derived from the observed level scheme of ^{141}Ho [24].

The wave function of ^{145}Tm can be composed from single-particle proton orbitals coupled to the ground and excited states of the even-even core [11]. To explain the observed partial-halflives of proton transitions within the spherical picture [27], the $I^\pi=11/2^-$ wave function should contain about 67% of the $\pi h_{11/2}\otimes 0^+$ and about 3.7% of the $\pi h_{7/2}\otimes 2^+$ configurations. The remaining 30% admixture is created from negative parity proton orbitals (l=3,5,7) coupled to the 2^+ core vibration. Since there is a non-negligible deformation expected from the 2^+ energy value as well as from recent data on neighbouring nuclei such as the proton-emitter ^{147}Tm [28, 29], the spherical estimations should be taken as "spherical reference values". More recently, models based on particle-core vibration coupling and accounting for non-spherical shapes have been developed [30, 31]. Here, he structure of the ^{145}Tm wave function and its decay process analyzed within Hagino's model [30, 11] are presented in Fig. 4. Similarly to the spherical reference description, the $\pi h_{11/2}\otimes 0^+$ forms about 56% of the wave function. The 1.4 MeV transition results from 3% admixture of $\pi h_{7/2}\otimes 2^+$. The $\pi h_{11/2}$ orbital

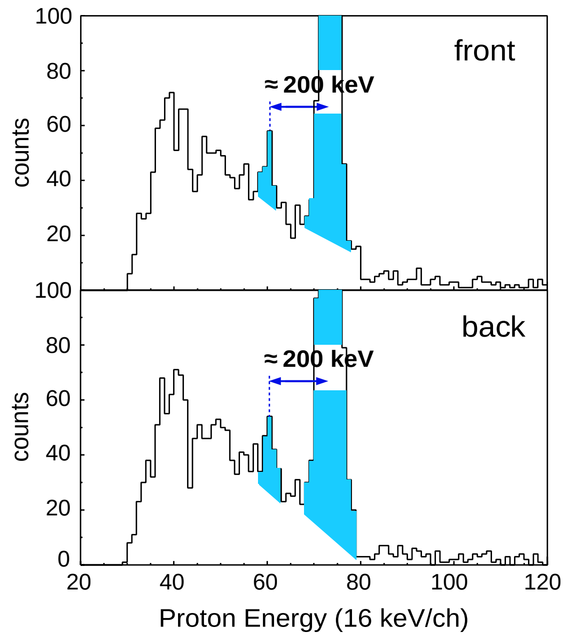

FIGURE 3. Fine structure in proton emission from ^{141gs}Ho. The 0.97 MeV proton lines, which are 0.2 MeV below dominating known transitions at 1.17 MeV, were observed in the energy spectra collected at the front and at back strips of the DSSD. The energy difference betweem proton lines fits perfectly to the excitation energy of the 2^+ state in ^{140}Dy [22, 23].

dominates the function, with an additional 40% of $\pi h_{11/2}$ coupled to 2^+ core vibration. The $\pi h_{11/2} \otimes 2^+$ component does not contribute substantially to the decay width. The calculated halflife of 3.0(4) μs is in an excellent agreement with the measured value of 3.1(3) μs and the predicted branching ratio of 5.7(3)% is slightly below the measured value of 9.6(15)%. Calculations of Davids and Esbensen [31] reproduce the $I_p(2^+)$ value and halflife for ^{145}Tm decay. The contribution of $\pi f_{7/2} \otimes 2^+$ to the wave function is calculated to be 4%, as in the spherical and Hagino's descriptions. However, the $\pi h_{11/2} \otimes 0^+$ component which dominates the wave function in the above models, is only about 33%. This discreapance might be caused by different parametrizations of the optical potential, resulting in the potential more "transparent" for tunelling protons.

The interpretation of ^{141}Ho decay is more complex. It was anticipated that ^{141}Ho is a highly deformed nucleus, with β_2 value near 0.3 [12, 13]. The equilibrium deformations calculated within macroscopic-microscopic approach [32] in the [β_2,β_4] space for the low-lying one-quasiproton states in ^{141}Ho are very similar, yielding deformations of $\beta_2 \approx$0.27 and $\beta_4 \approx$-0.07 [13]. Such deformations were also obtained in ref.[33]. Lower β_2 deformation values were suggested by the analysis of the level schemes of ^{141}Ho (β_2=0.25(4) [24]) and of ^{140}Dy (β_2=0.23-0.24 [22, 23]). However, even with β_2 set to 0.24 and β_4 around 0.04-0.05, the halflife of the $7/2^-$[523] ^{141}Ho ground-state calculated within the non-adiabatic model [34, 35] is about 10 times longer in comparison to the observed 4 ms [22]. Also, the $I_p(2^+)$ branching ratio is about 2%, above the observed

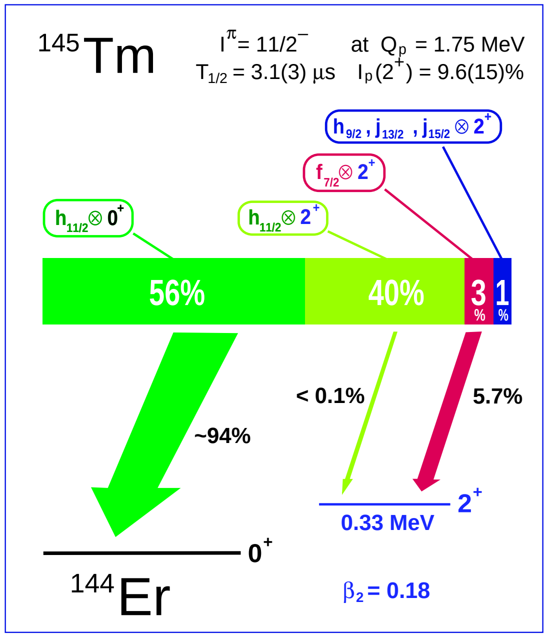

FIGURE 4. The wave function and proton emission widths for ^{145}Tm according to particle - core vibration coupling model of Hagino [11].

value 0.70(15)%.

Theoreticcally, the non-adiabatic model for proton radioactivity provides the microscopic description of the emission process and the underlying nuclear structure. It fully takes into account the coupling of the single-particle motion of the proton to the deformed nuclear core. It describes well the decay of the highly deformed emitter ^{131}Eu [5, 34, 35]. Likely, the assumption of the prolate shape described within the $[\beta_2,\beta_4]$ deformation space might not be adequate for ^{141}Ho. A new approach to the proton emission from ^{141}Ho was presented at this meeting by A.Kruppa [36]. Better agreement with experimental data is achieved, when the coupling of the ^{140}Dy ground-state band and an excited γ-band starting at about 500-600 keV is included in the non-adiabatic description. A different scenario, within the adiabatic model, was presented by Davids [37] pointing to the role of the deformed spin-orbit term and neglecting the strong Coriolis coupling term for the $7/2^-[523]$ state. More complete experimental data on the ^{140}Dy level scheme, and in particular the observation of fine structure in proton emission from the $1/2^+[411]$ isomeric state in ^{141}Ho should help the intepretation of the decay process.

This work was supported by the U.S. D.O.E. through Contracts No. DE-FG02-96ER40983, DE-FG05-88ER40407, DE-FG02-96ER40978, DE-FG02-96ER41006, DE-AC05-76OR00033, DE-FG02-96ER40963, by the Polish KBN Grants No. 2P03B 08617 and 2P03B 04516, by the Hungarian OTKA Grants No. T026244 and T029003, and by NATO Grant No. PST.GLG.977613. The Joint Institute for Heavy Ion Research is supported by its members, University of Tennessee, Vanderbilt University and Oak Ridge National Laboratory. ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

REFERENCES

1. Hofmann, S., *Radiochimica Acta* **70/71**, 93 (1995).
2. Woods, P.J. and Davids, C.N., *Annu. Rev. Nucl. Part. Sci.* **47**, 541 (1997).
3. Rykaczewski, K.P., *Eur. Phys. Jour.* **A 15**, 81 (2002).
4. Maglione, E. and Ferreira, L.S., *Eur. Phys. Jour.* **A 15**, 135 (2002) and refs. therein.
5. Sonzogni, A. A. et al., *Phys. Rev.* **C65**, 031303 (2002).
6. Ginter, T.N. et al., in *Proc. of First Int. Symposium on Proton-Emitting Nuclei (PROCON'99)*, ed. J.C. Batchelder, AIP **518**, p.83 (2002).
7. Ginter, T.N., PhD Dissertation, unpublished, Vanderbilt University, Nashville, TN (1999).
8. Gross, C.J. et al., *Nucl. Instrum. Methods Phys. Res.* **A450**, 12 (2000).
9. Ginter, T.N. et al., *Phys. Rev.* **C61**, 014308 (2000).
10. Batchelder, J.C. et al., *Phys. Rev.* **C57**, R1042 (1998).
11. Karny, M. et al., *Phys. Rev. Lett.* **90**, 012502 (2003).
12. Davids, C.N. et al, *Phys. Rev. Lett.* **80**, 1849-1852 (1998).
13. Rykaczewski, K. et al., *Phys. Rev.* **C60**, 011301 (1999).
14. Rykaczewski, K. P. et al., in *Proc. of Int. Conf. on Nuclear Structure "Mapping the Triangle"*, Wyoming, May 2002, **AIP 638**, p. 149 (2002).
15. Grzywacz, R.K. et al., in *Proc. of 3rd Int. Conf. on Exotic Nuclei and Atomic Masses (ENAM 2001)*, Hameenlinna, Finland, July 2001 Springer Verlag, p. 453 (2002)
16. Grzywacz, R.K., in *Proc. of Int. Conf. on Electromagnetic Separation of Nuclei (EMIS14th)*, British Columbia, May 2002, Nucl. Instr. Meth. in Phys. Res. **B204**, 649 (2003).
17. Grzywacz, R.K., in *Proc. of Second Int. Symposium on Proton-Emitting Nuclei (Procon'03)*, Legnaro, Italy, February 2003, E. Maglione and L.Ferreira (eds.)
18. Shapira, D., Lewis, T.A., and Hulett, L.D, *Nucl. Instrum. Methods Phys. Res.* **A454**, 409 (2000).
19. Hubbard-Nelson, B. et al., *Nucl. Instrum. Methods Phys. Res.* **A422**, 411 (1999) and *http://www.xia.com*
20. Casten,R.F., "Nuclear Structure from a Simple Perspective", 2nd ed., Oxford, NY, p. 297-330 (2000) and earlier refs therein.
21. Zamfir, V.N., private communication (1998).
22. Królas, W. et al., *Phys. Rev.* **C65**, 031303 (2002).
23. Cullen, D.M. et al., *Phys. Lett.* **B529**, 42 (2002).
24. Seweryniak, D. et al., *Phys. Rev. Lett.* **86**, 1458-1461 (2001).
25. Grodzins,L., *Phys. Lett.* **2**, 88 (1962).
26. Raman, S., et al., *At. Data Nucl. Data Tables* **78**, 1 (2001).
27. S. Åberg *et al., Phys. Rev.* **C56**, 1762 (1997), and *Phys. Rev.* **C58**, 3011 (1998).
28. Klepper, O., et al., *Zeit. Phys.* **A305**, 125 (1999).
29. Seweryniak, D., et al., *Phys. Rev.* **C55**, R2137 (1997).
30. Hagino, K., *Phys. Rev.* **C64**, 041304R (2001).
31. Davids, C.N. and Esbensen, H., *Phys. Rev.* **C64**, 034317 (2001).
32. Nazarewicz, W., *et al.*, *Nucl. Phys.* **A512**, 61 (1990).
33. Möller, P., et al., *At. Data Nucl. Data Tables* **66**, 131 (1997).
34. Kruppa, A.T., Barmore, B., Nazarewicz, W. and Vertse, T., *Phys. Rev. Lett.* **84**, 4549 (2000).
35. Barmore, B., Kruppa, A.T., Nazarewicz, W. and Vertse, T., *Phys. Rev.* **C62**, 054315 (2000).
36. Kruppa, A. and Nazarewicz, W., in *Proc. of Second Int. Symposium on Proton-Emitting Nuclei (Procon'03)*, Legnaro, Italy, February 2003, E. Maglione and L.Ferreira (eds.)
37. Davids, C.N., in *Proc. of Second Int. Symposium on Proton-Emitting Nuclei (Procon'03)*, Legnaro, Italy, February 2003, E. Maglione and L.Ferreira (eds.)