PROTON-RICH NUCLEI STUDIED WITH RISING*

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During the years 2006 to 2009, Rare Isotope Spectroscopic INvestigations at GSI (RISING) have focused on high-resolution γ-ray spectroscopy of exotic nuclear species at rest: following unambiguous discrimination and identification by the FRagment Separator (FRS) and its suite of detectors, the nuclei of interest were implanted in either a passive stopper or a stack of silicon detectors to allow for measurements of delayed ion–$\gamma(\gamma)$ or ion–β–$\gamma(\gamma)$ correlations. Results concerning experiments along the $N \sim Z$ line are summarised.

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1. Introduction

The relevance of isomeric or metastable states is an undisputed facet of nuclear structure investigations. Simply their existence but even more their decay modes continue to be valuable sources and constraints on contemporary models of the atomic nucleus. In fact, the combination of isotope-selective devices, high-resolution γ-ray spectroscopy, and pixellated charged-particle detection devices allows one to tag isomers and determine their often unusual and sometimes unexpected decay modes, which in turn reveals the first concise information on nuclei far from the line β stability — based upon samples of fewer than a thousand nuclei.

The isospin degree of freedom opens up, as soon as such investigations are directed at nuclei at or beyond the $N = Z$ line, thereby passing the doubly-magic fixed points ^{40}Ca and ^{56}Ni on the road to ^{100}Sn. Here, β-delayed

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γ rays are of specific interest as they delineate weak but often decisive decay paths relevant for the description of isospin symmetry and, more importantly, isospin-symmetry breaking [1]. Figure 1 highlights the various physics topics of the RISING Stopped-Beam campaign.

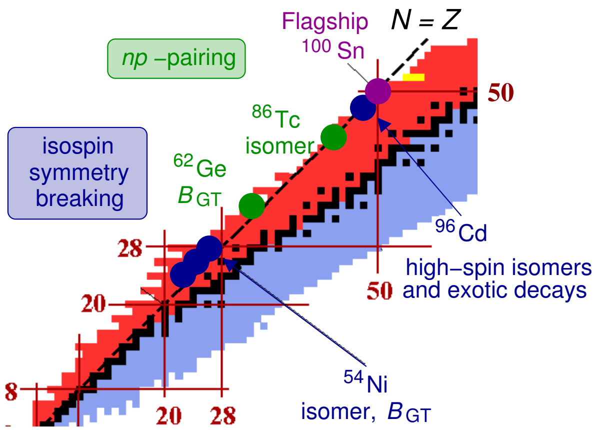

Fig. 1. Sketch of the chart of nuclides with the main isotopes of the $N \sim Z$ experiments within the RISING Stopped Beam Campaign marked.

2. Experiments and methods

The experiments discussed here have all been performed at the GSI Helmholtzzentrum für Schwerionenforschung GmbH at Darmstadt, Germany. Primary beams with intensities up to $\sim 10^9$ particles per second and energies of typically 0.5–1.0 GeV per nucleon are provided by the SIS18 and impinge on fragmentation targets at the entrance of the FRS. The latter transports and separates the isotopes of interest, with event-by-event identification of mass, A, and proton number, Z, ensured by its standard suite of detectors [2]. At the final focus of the FRS, the nuclei are implanted into either a passive piece of plastic or metal or stacks of double-sided silicon strip detectors [3], which are surrounded by 15 former Euroball Cluster detectors [4], *i.e.* a total of 105 large-volume germanium crystals. In conjunction with digital electronics, this set-up provides a world-unique combination of isotope selectivity and sensitivity for high-resolution γ-ray spectroscopy in the range 50 keV $\leq E_\gamma \leq$ 6 MeV [5]. A typical example, namely the γ decay of two isomers in ^{43}Ti, is depicted in Fig. 2.

More experimental details can also be found in Refs. [6, 7] and the respective physics papers referred to in the following sections.

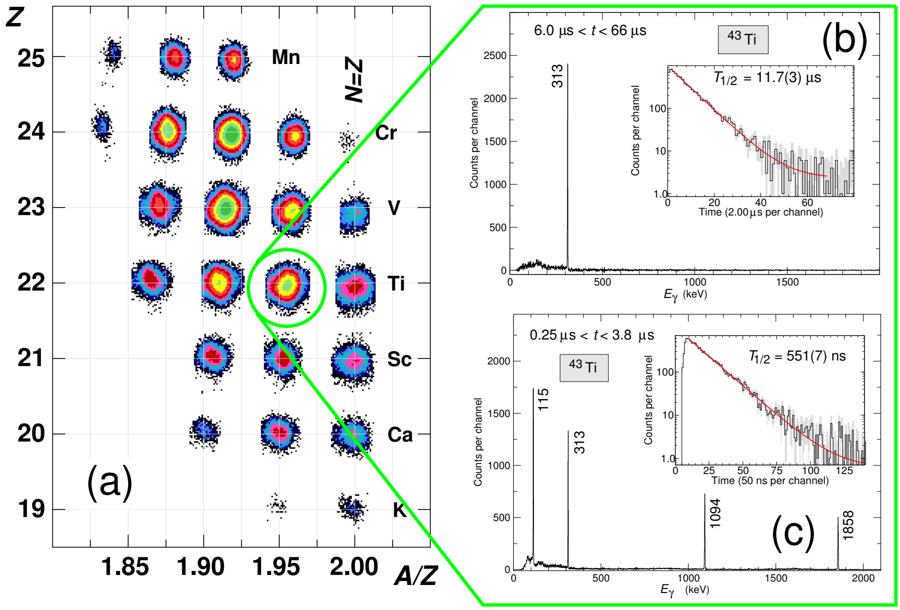

Fig. 2. (a) Example for an isotope-selective identification plot following the fragmentation of a 550-MeV/u ^{58}Ni beam. The γ-ray spectra (parts (b) and (c)) are correlated with at time $t = t_0$ implanted ^{43}Ti nuclei within different periods $[t_1, t_2]$. The insets provide the respective decay curves of the transitions depopulating the two isomeric states in ^{43}Ti.

3. Results and discussion

3.1. Mirror isomers near ^{56}Ni

The microscopic understanding of so-called mirror-energy differences (MED), *i.e.* differences in excitation energies of analogue states in mirror nuclei, has increased significantly throughout the last decade [1, 8]. The most reliable testing ground has been the fp-shell, and in particular nuclei located between ^{40}Ca and ^{56}Ni, where MED values call for an isospin-symmetry breaking part originating from the strong force, especially in the $T = 1$, $J = 2$ channel [9]. This proposal could be extended by the identification of a core-excited 10^+ isomer in ^{54}Ni, which mirrors a well-known 10^+ isomer in ^{54}Fe [10]. Moreover, this high-spin isomer revealed a rather intense discrete-energy $\ell = 5$ proton decay branch into the first excited $I^\pi = 9/2^-$ state of ^{53}Co, thereby taking this decay mode home to its origins [11, 12]. The high-statistics experiment on ^{54}Ni allowed also the discrimination of a short-lived $3/2^-$ mirror isomer in ^{53}Co itself: This is due to an *in situ* production inside the passive beryllium stopper by means of secondary fragmentation [13].

Another facet of this region of the chart of nuclides is the possibility to do theoretical 'shell-model spectroscopy', *i.e.* a number of reliable and profound shell-model interactions allow for detailed studies of the fp-shell nuclei. Focusing on states with rather pure configurations predicted by *all* such interactions allows us, for example, to examine effective charges in greater detail. Figure 3 provides the present status, which strongly hints at an orbital dependency [14, 15, 16, 17].

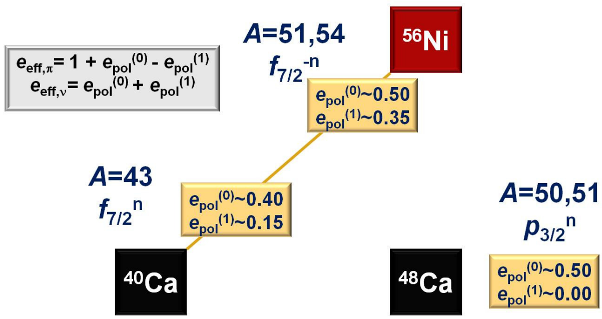

Fig. 3. Effective charges needed to reproduce decay strengths of specific states in the fp shell-model space. See text and Refs. [14, 15, 16] for details.

3.2. Gamow–Teller strength and charge exchange reactions

A fascinating way to probe isospin symmetry is to compare and relate Gamow–Teller (GT) strengths in β decay with those measured via charge-exchange reactions. Assuming a set of isobaric analogue states, GT decays between parent mirror nuclei (*e.g.*, ^{54}Ni and ^{54}Fe) and a common daughter nucleus (here: ^{54}Co) should reveal identical strength — in the absence of isospin mixing. Recent high-resolution (^{3}He,t) charge exchange reactions have been performed at RCNP Osaka [18, 19] on a series of $T = 1$ fp-shell target nuclei, and the corresponding $\beta\gamma$ coincidence decay measurements on ^{42}Ca, ^{46}Cr, ^{50}Fe, and ^{54}Ni have been performed within the RISING Active-Stopper campaign in 2008. Preliminary results are summarised in Ref. [20] and show, amongst others, the experimental RISING power by allowing the clean observation of weak γ-ray transitions with energies $E_\gamma > 5$ MeV.

3.3. Neutron–proton pairing in mass $A = 62$

The search for enhanced proton–neutron pair correlations in $N \sim Z$ nuclei continues to be of interest. Within the RISING Active-Stopper campaign, the β decay of the $N = Z - 2$ nucleus ^{62}Ge was studied, with the focus lying on GT branches into excited 1^+ states in the odd–odd $N = Z$ daughter ^{62}Ga [21] next the dominant $0^+ \rightarrow 0^+$ superallowed Fermi decay.

The idea is visualised in Fig. 4: In light nuclei, considerable GT strength can by explained by the Wigner SU(4) symmetry, which is broken by the spin-orbit splitting in heavier nuclei. This tends to lead to a fragmentation of GT strength but might be restored by a proton–neutron condensate. Arising from an IBM-4 concept [22,23], a survival of such significant proton–neutron pair correlations in medium-mass nuclei may result in enhanced GT transitions into the low(est) lying $T = 0$, $I^\pi = 1^+$ states. This is due to a predicted low-lying collective 1^+ neutron–proton state in the odd–odd $N = Z$ nucleus, which is fed by a collective, superallowed GT transition when changing either a $T = 1$ *pp*-boson into a $T = 0$ *pn* boson, or a $T = 0$ *pn*-boson into a $T = 1$ *nn* boson.

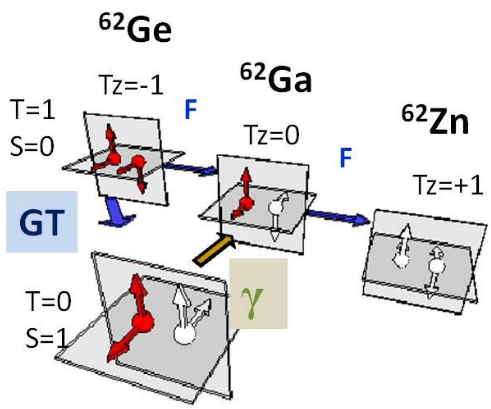

Fig. 4. Scheme of the decay path of the 0^+ ground state of the even–even $T_z = -1$ nucleus ^{62}Ge: Either via a superallowed Fermi decay into the ground state of ^{62}Ga, or a Gamow–Teller 'bypass' followed by β-delayed $1^+ \to 0^+$ γ-ray transitions [24].

In the experiment, about 16000 ^{62}Ge nuclei were implanted into the RISING Active Stopper [3]. Previous half-life measurements are nicely confirmed by correlations with subsequent β decays of ^{62}Ga. A number of γ rays are observed in coincidence with the β decays of ^{62}Ge as well, but there is no apparent preference in feeding the lowest known 1^+ state in ^{62}Ga [24].

3.4. Isomers in odd–odd $N = Z$ nuclei

Using the fragmentation of a primary ^{107}Ag beam, the low-lying structures of a number of $N \sim Z$ nuclei in the mass $A = 80$–90 regime have been determined. The main focus lies on the competition of isospin $T = 0$ and $T = 1$ states in the hitherto heaviest odd–odd $N = Z$ nuclei with known excited states: ^{82}Nb and ^{86}Tc [25,26,27].

As shown in Fig. 5 (a), γ-ray transitions at 124, 418, and 638 keV are associated with the decay of an isomeric state in ^{82}Nb. They closely resemble the $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade in the $T_z = 1$ neighbour ^{82}Zr [28], when starting from an $I = 5$ state depopulated by the 124-keV low-energy transition. This interpretation is supported by, for instance, Total Routhian Surface calculations, which predict rather soft triaxial shapes for both ^{82}Nb and ^{82}Zr. Though similar, the spin and parity of the isomeric state in ^{86}Tc is somewhat less well defined, *i.e.* there are possible solutions for both a 6^+ (K-isomer) or 5^- scenario [27, 29]. Nevertheless, also in the case of ^{86}Tc the $T = 1$ states are clearly favoured in energy, providing a consistent picture for a series of odd–odd $N = Z$ nuclei in the $f_{5/2}pg_{9/2}$ shell.

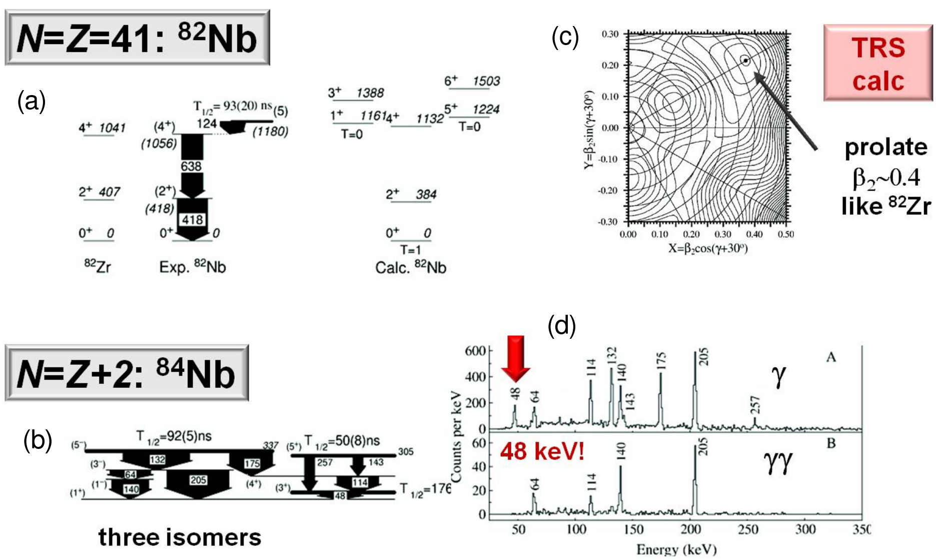

Fig. 5. Isomeric decay schemes of $N = Z = 41$ ^{82}Nb (a) and its $N = Z + 2 = 43$ odd–odd neighbour ^{84}Nb (b). Part (c) illustrates a shape prediction of a total Routhian surface (TRS) calculation for ^{82}Nb. ^{84}Nb-ion correlated, delayed γ-ray and $\gamma\gamma$-coincidence spectra are displayed in part (d). Taken from Ref. [29].

In addition to the two $N = Z$ nuclei, a number of isomeric states are detected in neighbouring nuclei such as ^{84}Nb and ^{87,88}Tc [29]. In combination with existing information from fusion-evaporation reaction studies [30, 31, 32] further light is shed on their low-lying structure: Shape hindrance is thought responsible for the isomerism in ^{87}Tc, while shell-model calculations propose a low-lying isomeric 4^+ state consistent with the observations in ^{88}Tc. The low-lying decay scheme of ^{84}Nb comprises three isomeric states and is shown in Fig. 5 (b). Compared to $N = Z$ ^{82}Nb, the striking but expected difference is the missing np-pairing gap. Secondly, the γ-ray spectra on the right stress the RISING experimental access to low-energy γ-rays and $\gamma\gamma$-coincidences [29].

3.5. High-spin isomers south–west of ^{100}Sn

High-spin isomers in $N \sim Z$, mass $A \geq 90$ nuclei are a rich source of information for the shell structure at and near ^{100}Sn. Due to the strong neutron–proton pairing interaction matrix elements, the underlying origins of these isomers are aligned configurations of the type $\nu(g_{9/2})^{-n} \times \pi(g_{9/2})^{-m}$. The most prominent example is the anticipated 21^+ state in ^{94}Ag with $n = m = 3$, which is revealed to have a half-life of $T_{1/2} \sim 0.4$ s and various decay modes [33, 34, 35]. Negative-parity isomers typically involve an odd particle or hole in the $p_{1/2}$ orbital as observed in, for example, ^{94}Pd [36, 37].

Another set of isomers, which are subject to core-excited states, has also been found in the course of the recent RISING campaign. Examples are anticipated 12^+ and 19^+ states in ^{98}Cd [38, 39] and ^{96}Ag [40], respectively. Their origin is similar to the 10^+ states in ^{54}Ni and ^{54}Fe discussed in Sec. 3.1. This is illustrated in Fig. 6 (a). Not only do the energies of the core-excited states tell us about the size of the magic shell gaps at particle numbers 28 and 50, respectively, but the competition between $E2$ and $E4$ branches provides access to the details of the wave functions hence shell-model interactions. Last but not least, the RISING efficiency for high-energy γ-rays is vital for the observation, as can be seen from the delayed γ-ray spectrum attributed to ^{96}Ag in Fig. 6 (b).

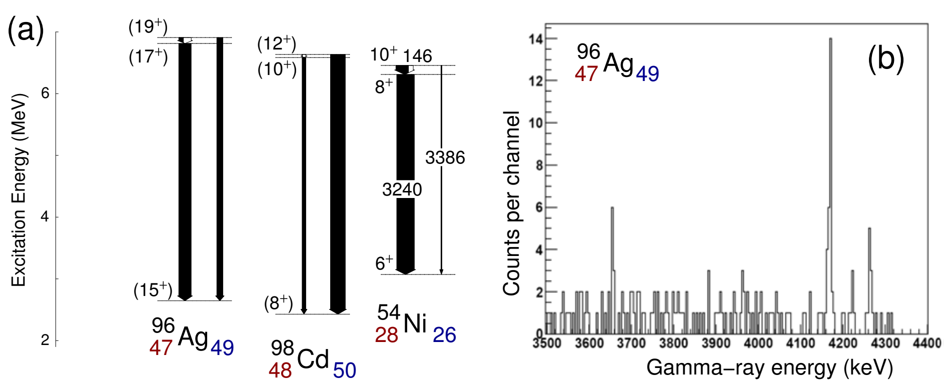

Fig. 6. (a) Comparison of core excited states in ^{96}Ag [40], ^{98}Cd [38, 39], and ^{54}Ni [10]. (b) High-energy portion of the γ-ray spectrum in delayed coincidence with implanted ^{96}Ag nuclei illustrating the respective $(17^+) \to (15^+)$ $E2$ and $(19^+) \to (15^+)$ $E4$ transitions in ^{96}Ag.

3.6. Flagging ^{100}Sn

A flagship endeavour was undertaken in 2008 to collect the hitherto most comprehensive knowledge on the decay of the $N = Z = 50$ nucleus ^{100}Sn. Led by the group at TU Munich, the collaboration combined the RISING γ-ray spectrometer with the Silicon IMplantation detector and Beta Absorber (SIMBA) [41]. Compared to all previous experimental investigations [42,43,44], a rate increase in the production of ^{100}Sn from about 1/day to roughly 1/hour was achieved, and a production cross-section of 5–10 pb derived. Due to the significantly increased primary ^{124}Xe beam intensities at GSI, the decay of more than 250 ^{100}Sn nuclei can be detailed [45].

Being the heaviest, stable, self-conjugate doubly-magic nucleus, information on ^{100}Sn is important not just for conventional shell-model approaches: the β^+ decay of ^{100}Sn surely resembles the most pure Gamow–Teller spin-flip transition on the chart of nuclei, namely an almost exclusive branch into a single low-lying $\pi(g_{9/2})^{-1} \times \nu(g_{7/2})^1$ 1^+ state in the daughter ^{100}In, which moreover lies inside the β-decay energy window.

Preliminary results provide a more precise value of the half-life, $T_{1/2}$, which is consistent with earlier numbers [42, 44]. For the first time, a β spectrum is derived, which gives rise to a world-record value of $\log ft < 3$ and, hence, a high $B_{\rm GT}$ strength. Five γ-ray transitions are observed in correlation with the ^{100}Sn β decays, the energies of which call for at least two parallel γ-ray cascades in ^{100}In. The possibility of an isomeric $I^\pi = 6^+$ state in ^{100}Sn has been investigated as well, though unfortunately without obvious success. Eventually, the anticipated isomer decays by direct proton emission as seen in the case of ^{54}Ni [10].

4. Summary and outlook

Undoubtedly, the RISING Stopped Beam campaign has and will significantly advance the understanding of nuclear structure along the $N = Z$ line. Particularly isospin symmetry breaking, *np*-pairing, and extended shell-model studies near doubly-magic ^{56}Ni and ^{100}Sn have been at the focus, and some of the results for the heavier nuclei relate to aspects of nuclear astrophysics. Investigations of the fragmentation reaction process itself have been and will be undertaken as well with the existing $N \sim Z$ data sets [46,47], but cannot be detailed any further here. The same is true for the majority of physics issues, which could only be touched upon briefly in this summary. Details can be found in the respective published or soon to be published manuscripts and PhD theses.

In conclusion, the basis of the great success of this RISING campaign lies in the unprecedented and unique capabilities of combining high-intensity, relativistic primary beams with an event-by-event 'isotope-identifier' followed by a highly efficient, high-resolution spectroscopy set-up with decent granularity.

While the RISING project came to an end in 2009, its successor PRESPEC is in place at the moment, which has two main aims: to prepare the nuclear structure community for the opportunities at FAIR in the mid-term future, while using existing and optimising new equipment to tackle more of the unknowns on the chart of nuclei — the physics of the PRESPEC Decay Campaign opened with a workshop as early as January 2011 in Brighton [48].

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REFERENCES

[1] M.A. Bentley, S.M. Lenzi, *Prog. Part. Nucl. Phys.* **59**, 497 (2007).
[2] H. Geissel *et al.*, *Nucl. Instrum. Methods* **B70**, 286 (1992).
[3] R. Kumar *et al.*, *Nucl. Instrum. Methods* **A598**, 754 (2009).
[4] J. Eberth *et al.*, *Nucl. Instrum. Methods* **A369**, 135 (1996).
[5] S. Pietri *et al.*, *Nucl. Instrum. Methods* **B261**, 1079 (2007); *Acta Phys. Pol. B* **38**, 1255 (2007).
[6] P.H. Regan *et al.*, *Nucl. Phys.* **A787**, 491c (2007).
[7] D. Rudolph *et al.*, *Eur. Phys. J. Special Topic* **150**, 173 (2007).
[8] J. Ekman, C. Fahlander, D. Rudolph, *Mod. Phys. Lett.* **A20**, 2977 (2005).
[9] A.P. Zuker *et al.*, *Phys. Rev. Lett.* **89**, 142502 (2002).
[10] D. Rudolph *et al.*, *Phys. Rev.* **C78**, 021301(R) (2008).
[11] K.P. Jackson *et al.*, *Phys. Lett.* **B33**, 281 (1970).
[12] J. Cerny *et al.*, *Phys. Lett.* **B33**, 284 (1970).
[13] D. Rudolph *et al.*, *Eur. Phys. J.* **A36**, 131 (2008).
[14] R. Hoischen *et al.*, *J. Phys. G* **38**, 035104 (2011).
[15] R. du Rietz *et al.*, *Phys. Rev. Lett.* **93**, 222501 (2004).

[16] J.J. Valiente Dobón *et al.*, *Phys. Rev. Lett.* **102**, 242502 (2009).
[17] H.L. Ma *et al.*, *Phys. Rev.* **C80**, 014316 (2009).
[18] T. Adachi *et al.*, *Nucl. Phys.* **A788**, 70c (2007).
[19] Y. Fujita *et al.*, *J. Phys. G* **35**, 014041 (2008).
[20] F. Molina *et al.*, *AIP Conf. Proc.* **1265**, 49 (2010).
[21] D. Rudolph *et al.*, *Phys. Rev.* **C69**, 034309 (2004).
[22] F. Iachello, Proc. Int. Conf. Perspectives for the IBM, Padova, Italy, 1994.
[23] P. van Isacker, *J. Phys. Conf. Series* **20**, 131 (2005).
[24] A. Gadea *et al.*, to be published.
[25] A.B. Garnsworthy *et al.*, *Acta Phys. Pol. B* **38**, 1265 (2007).
[26] L. Cáceres *et al.*, *Acta Phys. Pol. B* **38**, 1271 (2007).
[27] A.B. Garnsworthy *et al.*, *Phys. Lett.* **B660**, 326 (2008); *Erratum-ibid.* **B668**, 460 (2008).
[28] D. Rudolph *et al.*, *Phys. Rev.* **C56**, 98 (1997).
[29] A.B. Garnsworthy *et al.*, *Phys. Rev.* **C80**, 064303 (2009).
[30] C.J. Gross *et al.*, *Phys. Rev.* **C43**, R5 (1991).
[31] N. Mărginean *et al.*, *Eur. Phys. J.* **A4**, 311 (1999).
[32] D. Rudolph *et al.*, *J. Phys. G* **17**, L113 (1991).
[33] M. La Commara *et al.*, *Nucl. Phys.* **A708**, 167 (2002).
[34] C. Plettner *et al.*, *Nucl. Phys.* **A733**, 20 (2004).
[35] I. Mukha *et al.*, *Phys. Rev. Lett.* **95**, 022501 (2005).
[36] R. Wadsworth *et al.*, *Acta Phys. Pol. B* **40**, 611 (2009).
[37] T. Brock *et al.*, *Phys. Rev.* **C82**, 061309 (R).
[38] A. Blazhev *et al.*, *J. Phys. Conf. Series* **205**, 012035 (2010).
[39] N. Braun *et al.*, to be published.
[40] P. Boutachkov *et al.*, to be published.
[41] Ch. Hinke, GSI Dissertation, 2010-15.
[42] R. Schneider *et al.*, *Z. Phys.* **A348**, 241 (1994).
[43] M. Lewitowicz *et al.*, *Phys. Lett.* **B332**, 20 (1994).
[44] D. Bazin *et al.*, *Phys. Rev. Lett.* **101**, 252501 (2008).
[45] Ch. Hinke *et al.*, to be published.
[46] S. Myalski *et al.*, *Acta Phys. Pol. B* **38**, 1277 (2007).
[47] R. Hoischen *et al.*, to be published.
[48] `http://npg.dl.ac.uk/PRESPEC-11`