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New information on r-process nuclei

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New information on r-process nuclei

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Abstract. The current status of nuclear-structure measurements on medium-heavy isotopes relevant to r-process nucleosynthesis is briefly reviewed. Here, the main focus is put on the region around the doubly-magic nucleus ^{132}Sn , where first experimental evidence for a weakening of the $N=82$ shell strength is presented. This new phenomenon leads to improved predictions of astrophysical observables like the solar-system isotopic r-abundances and the recent Ba – U elemental abundances of ultra-metal-poor neutron-capture-rich halo stars.

Introduction

Relative to other fields, astrophysics – and in particular explosive nucleosynthesis – is probably unique in its requirements that a very large number of physical environments be modeled to achieve a satisfactory description of the phenomena under study. On the nuclear level, cross sections, nuclear masses and decay properties are but a few examples of quantities that are of paramount importance in astrophysical models. Because nuclei of extreme N/Z composition, quite different from what has so far been studied on earth, exist in explosive stellar environments, an understanding of their nuclear-structure properties presents a continuing, stimulating challenge to the experimental and theoretical nuclear-structure community.

For example, only some 15 years ago, astrophysicists still believed that nuclear-structure information on isotopes in the r-process path would never become available from terrestrial experiments. However, already a few years later in 1986, a new area in nuclear astrophysics started with the identification of the first two classical, neutron-magic "waiting-point" isotopes [1] $^{80}\text{Zn}_{50}$ and $^{130}\text{Cd}_{82}$ [2–4].

Since then, considerable progress has been achieved in the study of neutron-rich medium- to heavy-mass nuclei at different laboratories (e.g. ILL/OSTIS, BNL/TRISTAN, Nyköping/OSIRIS, CERN/ISOLDE, GANIL/LISE, GSI/FRS, JYFL/IGISOL, LLN/LISOL, Mainz/SISAK, and the Eurogam and Gammasphere Spontaneous-Fission Collaborations), using various production, separation and detection methods. However, due to the generally very low production yields, the occurrence of isobar, multi-charged ion and molecular-ion contaminations from

chemically non-selective ionization modes, or because of the application of non-selective detection methods, *direct* information on isotopes lying in the r-process path(s) could be obtained but in a few cases, like e.g. $^{79}\text{Cu}_{50}$, $^{84}\text{Ga}_{53}$ or $^{85}\text{Ge}_{53}$ [5]. From the majority of investigations, originally dedicated to study nuclear-structure developments as a function of isospin, 'only' *indirect* – but nevertheless also important – information for r-process calculations can be deduced (see, e.g. [6–11]). In this context, we would like to remind the reader of the fascinating phenomenon of the *sudden onset and saturation of ground-state deformation at $N=60$* (see, e.g. [12–14]), which had in fact led to the first 'astrophysical request' of $N=82$ shell quenching [7].

Because of the severe experimental problems to identify r-process nuclei, recent progress has undoubtedly benefitted from the **selectivity** in their production and detection, by applying e.g. Z-selective laser ion-source (LIS) systems, isobar separation or multifold-coincidence techniques.

Recent experiments

There are mainly three mass regions, where at present nuclear-structure information is of particular astrophysical interest. The first is the *r-process seed* region which seems to be not well understood (see, e.g. [15,16]), involving very neutron-rich Fe-group isotopes up to the double-magic nucleus $^{78}\text{Ni}_{50}$. Recent spectroscopic results can, for example, be found in [17–20]. The second region is that of far-unstable nuclei around $A \simeq 115$. Here, most r-process calculations show a pronounced *r-abundance trough*, which is believed to be due to nuclear-model deficiencies at and beyond $N=72$ mid-shell (see, e.g. [7,9,10]). Recent experimental information can, for example, be found in [14,21–24]. The third region of interest is that around the *double-magic nucleus* ^{132}Sn . Apart from astrophysical importance (formation of the $A \simeq 130$ peak of the solar-system r-abundance distribution ($N_{r,\odot}$) [7,11]), this region is of considerable shell-structure interest. The far-unstable isotope $^{132}_{50}\text{Sn}_{82}$ itself, together with the properties of the nearest-neighbour single-particle ($^{133}_{51}\text{Sb}_{82}$ and $^{133}_{50}\text{Sn}_{83}$) and single-hole ($^{131}_{50}\text{Sn}_{81}$ and $^{131}_{49}\text{In}_{82}$) nuclides are essential for tests of the shell model, and as input for any reliable future microscopic nuclear-structure calculations towards the neutron drip-line.

Because of this importance and the recent improvements in laser ion-source (LIS) technology to provide clean beams of these exotic nuclei, in the following, we will focus on new spectroscopic investigations around ^{132}Sn [25–32]. The bulk of the known data in this region has been obtained from β -decay spectroscopy at the mass-separator facilities OSIRIS and ISOLDE.

The structures of ^{131}Sn (ν -hole) and ^{133}Sb (π -particle) are fairly well known since more than a decade. More recently, the ν -particle states $2f_{7/2}$ (g.s.), $3p_{3/2}$ (854 keV), $1h_{9/2}$ (1561 keV) and $2f_{5/2}$ (2005 keV), as well as tentatively also the $3p_{1/2}$ -particle (1655 keV) and the $1h_{11/2}$ -hole (≈ 3700 keV) states in $^{133}\text{Sn}_{83}$ have been identified by measuring γ -rays in coincidence with delayed neutrons (d.n.) of

FIGURE 1. Broad-band laser frequency scans for ^{123}Ag and ^{127}Ag (left side) using d.n.-counting. Both distributions are consistent with the typical HF-splitting of a $\pi g_{9/2}$ configuration. As shown in the right part of this figure, a d.n.-decay measurement at an off-center frequency at $A=129$ (i.e. at maximum $\pi g_{9/2}$ yield; as indicated by the open circle in the ^{127}Ag curve) permitted the identification of laser-ionized ^{129}Ag $\pi g_{9/2}$ decay on top of the isobar activities from the two ^{129}In isomers which are due to surface ionization.

^{134}In decay [25]. From these data, valuable information on the spin-orbit splitting of the 2f-orbital and tentatively the 3p-state splitting was obtained. These results were compared to mean-field and HFB predictions, and it was found that none of the potentials currently used in *ab initio* shell-structure calculations was capable of properly reproducing the ordering and spacing of these states (see, e.g. [33], where also possible astrophysical consequences are given). Of particular interest in this context are the surprisingly low-lying $\nu p_{3/2}$ - and $\nu p_{1/2}$ -states in ^{133}Sn . According to the standard Nilsson model [34], for example, they are expected at 2.89 MeV and 4.36 MeV, respectively. Such lowering of the energies of low-j orbitals has recently been predicted as a *neutron-skin* phenomenon to occur only near the neutron drip-line (see, e.g. [35]), but certainly not yet in $(N_{\text{mag}}+1)^{133}\text{Sn}$ which is still neutron-bound by $S_n \simeq 2.5$ MeV. Nevertheless, following the suggestion of Dobaczewski [35], we have modified the Nilsson potential by reducing the strength of the l^2 -term, in order to study its effect on different orbitals. And indeed, this procedure led to the desired change in the position and even the ordering of the ν -particle states beyond $N=82$, and allowed at least a qualitative reproduction of the experimental observation of low-lying low-j and high-lying high-j orbitals in ^{133}Sn .

With these new data, the ^{132}Sn valence-nucleon region is nearly complete. The only missing information are the π -hole states in $^{131}_{49}\text{In}$, which can in principle be studied through β -decay of the very exotic nucleus $^{131}\text{Cd}_{83}$. Recent LIS developments at Mainz [37] and CERN/ISOLDE, using a novel frequency-tripling technique for the Z-selective resonance ionization of Cd, indeed offer the possibility to perform such an experiment. First test measurements on neutron-rich Cd isotopes with this LIS system are already scheduled for Oct. 1998.

Another recent application of a chemically selective LIS at the ISOLDE facility are the spectroscopic measurements of neutron-rich Ag isotopes by a Mainz–Maryland–Troitzk–CERN collaboration [30–32]. Using an improved version of the LIS system described in [38] together with new microgating procedures [39], d.n.-counting and γ -ray spectroscopy could be performed up to 58-ms $^{128}\text{Ag}_{81}$. This approach was of considerable assistance in minimizing the activities from (unavoidable) surface-ionized In and Cs isobars. Moreover, the identification of the long searched waiting-point isotope $^{129}\text{Ag}_{82}$ was only possible by using the additional ‘selectivity’ of the spin- and moment-dependent hyperfine (HF) splitting to enhance the ionization of the $\pi g_{9/2}$ g.s.-decay (see Fig. 1).

The laser response to HF-splitting was calibrated on the stable $J^\pi=1/2^-$ ^{107}Ag whose magnetic moment is small ($\mu=-0.11$ n.m.) and on the radioactive $J^\pi=7/2^+$ isomer that has a large moment of $\mu=4.4$ n.m. (see [32,40]). Subsequently, the d.n.-activities were measured as a function of laser frequency for ^{122}Ag up to ^{127}Ag . As examples, the results for the two odd-mass isotopes ^{123}Ag and ^{127}Ag are shown in the left part of Fig. 1. Except ^{122}Ag , all other isotopes show – apart from the expected small isotope shift – the same pattern, where the moment of the odd $g_{9/2}$ -proton is the dominant source of HF-splitting.

For ^{122}Ag , a different pattern was observed (see Fig. 2). Previous decay-studies of this isotope had indicated the presence of both low- and high-spin isomers [41]. And indeed, apart from the highly split peak that might be associated with a $(\pi g_{9/2}-\nu h_{11/2})_9-$ configuration, another narrow peak shows up in the center that could arise from the $(\pi p_{1/2}-\nu d_{3/2})_1-$ configuration. Subsequently, both d.n.- and γ -decay from ^{122}Ag was studied also as a function of laser frequency. As is evident from the partial γ -spectra shown in the lower part of Fig. 2, when the laser is set at the center of the frequency scale, γ -rays from both isomers can be observed. However, when the laser frequency is shifted away from the center (to 35 units), ionization of the low-spin isomer is suppressed, and the γ -spectrum indicates that only the decay of the high-spin isomer is observed. Similarly, when following the d.n.-decay curves as a function of laser frequency, different half-lives are obtained which represent varying admixtures of the two isomers. From a preliminary analysis, we get an approximate half-life of the low-spin isomer of $T_{1/2}\simeq 550(50)$ ms and a value of $T_{1/2}\simeq 200(50)$ ms for the high-spin isomer of ^{122}Ag [42]. This experiment clearly demonstrates the sensitivity of ionization to laser frequency and marks the first observation of separation of short-lived isomers by this technique.

An important nuclear-physics quantity for r-process calculations (in particular for the build-up, the shape and the matter flow out of the $A\simeq 130$ $N_{r,\odot}$ -peak) is the β -decay half-life of the $N=82$ waiting-point isotope ^{129}Ag , sitting just below ^{130}Cd . QRPA calculations using different Q_β -values and single-particle wave functions resulted in decay rates between 15 ms and 170 ms [6,7,43]. This had left large uncertainties in the reproduction of the $A\simeq 130$ peak when based on the simplistic assumption of $N_{r,\odot}\times\lambda_\beta\approx\text{const.}$ (see, e.g. Fig. 4 in [44] and Fig. 1 in [11]).

Figure 2. Portions of γ -ray spectra of the decay of ^{122}Ag isomers. The upper spectrum was taken with the laser frequency set at the center peak (44 units; see insert upper right part), and can be compared with the lower spectrum obtained at an off-center frequency (35 units). The γ -ray at 798 keV has been assigned to the $2_2^+ \rightarrow 2_1^+$ transition (see insert upper left part), whereas the line at 759 keV corresponds to the decay of the 4_1^+ level to the 2_1^+ state [41].

Previous attempts [30] to observe d.n.-decay of ^{129}Ag had been performed with the (broad-band) lasers centered with respect to the mean frequency for the stable $\pi p_{1/2}$ ^{107}Ag . After the observation of enhanced ionization of the $\pi g_{9/2}$ level at an off-center frequency, a new experiment was performed with the laser setting at the peak value observed for ^{127}Ag (see left part of Fig. 1). This approach together with the microgating procedure [39], finally permitted the unambiguous identification of d.n.-decay from $\pi g_{9/2}$ ^{129g}Ag (see right part of Fig. 1). The half-life of 46^{+5}_{-9} ms is in very good agreement with the recent QRPA prediction of 47 ms [43], but is lower than the 'astrophysical requirement' of ≈ 130 ms [44]. However, that estimate is for an overall *average* half-life that would also include contributions from β -decay of a possible $\pi p_{1/2}$ isomer in ^{129}Ag . With the QRPA model of [45], it is possible to calculate the Gamow-Teller decay for such an isomer to $T_{1/2} \approx 320$ ms. When including an estimate for the expected first-forbidden strength (extrapolated from the decay of the $J^\pi = 1/2^-$ isomer in isotonic ^{131}In), a minimum value of $T_{1/2} \approx 125$ ms is suggested. And, indeed, a careful reexamination and comparison of the $A=129$ d.n.-decay curve (taken with the laser at central frequency) with the pure ^{129}In curve from a laser-off run, gave a first indication of a 'longer-lived' ^{129}Ag d.n.-component with a half-life of roughly 160 ms. Now, it will be important to use isomer-specific laser ionization in combination with isobar separation at ISOLDE to ascertain the existence of this $\pi p_{1/2}$ isomer.

As an extension of our earlier γ -spectroscopic work [31], we have also studied lev-

FIGURE 3. Systematics of the first 2^+ levels in neutron-rich ^{46}Pd to ^{54}Xe isotopes (left part); and $E(4^+)/E(2^+)$ ratios (right part).

els of even-even ^{126}Cd and ^{128}Cd from the decays of 95-ms ^{126}Ag and 58-ms ^{128}Ag . While for $^{126}\text{Cd}_{78}$ still 8 out of 12 γ -lines were placed in a partial level scheme (see, e.g. Fig. 5 in [32]), for $^{128}\text{Cd}_{80}$ so far only three lines could be assigned unambiguously, the two strongest corresponding to the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions. Our new results are shown in Fig. 3, together with known $E(2^+)$ and $E(4^+)/E(2^+)$ level systematics of neighbouring even- Z elements. The $E(4^+)/E(2^+)$ ratio for the 4n-hole nuclide ^{126}Cd is 2.25, a value almost unchanged relative to that for the 6n-hole isotope ^{124}Cd . Already this static ratio is in contrast to the larger reduction observed for the $Z=52$ isotones ^{128}Te and ^{130}Te . For the new 2n-hole nuclide ^{128}Cd , the energy of the first 2^+ state at 645 keV is even **lower** than the $E(2^+)$ of 657 keV in ^{126}Cd , and also the $E(4^+)/E(2^+)$ ratio of 2.22 is only insignificantly smaller than those in ^{124}Cd and ^{126}Cd . As can be seen from the right side of Fig. 3, this trend for the $Z=48$ isotopes clearly deviates from that of the $Z=50$ (Sn), 52 (Te) and 54 (Xe) isotones. This observation can be interpreted as a first direct experimental indication of a weakening of the $N=82$ shell strength below ^{132}Sn . A search for the $E(2^+)$ in $N=82$ ^{130}Cd is planned for the next Ag-run at ISOLDE.

Given this highly interesting result, one may have a look into existing data for additional 'hidden' or so far unrecognized signatures of shell quenching in this mass region. And indeed, first qualitative evidence for such a phenomenon comes from a comparison of the measured $T_{1/2} \simeq 195$ ms of $^{130}\text{Cd}_{82}$ [4] with QRPA predictions. When applying Q_β -values from the 'unquenched' mass models FRDM [43] and ETFSI-1 [46], theoretical $T_{1/2}$ values of 1.12 s and 674 ms are obtained, respectively. However, with the 'quenched' mass formulae HFB/SkP [9] and ETFSI-Q [47], shorter values of 246 ms and 364 ms, respectively, are derived which are in better agreement with experiment. Another, more direct indication is given by the measured masses in the ^{132}Sn region [48,27]. As can be seen from Fig. 4, between ^{50}Sn and ^{48}Cd there is a significant change in the trend of the experimental and theoretical mass differences (normalized to the FRDM predictions, $M_i - M_{\text{FRDM}}$). Clearly, for the Cd isotopic chain the best agreement with the measured masses is

FIGURE 4. Experimental and theoretical mass differences for ^{50}Sn and ^{48}Cd isotopes normalized to FRDM values ($M_i - M_{\text{FRDM}}$).

obtained with the 'quenched' ETFSI-Q.

Reproduction of r-abundances

Mainly as a result of the improved nuclear-physics input, our site-independent r-process parameter studies have revealed that the entire isotopic $N_{r,\odot}$ pattern cannot be reproduced by assuming a global steady flow. Instead, even in a single astrophysical event (e.g., a SN II) requires a superposition of a multitude of components (minimum three) with different neutron densities or equivalently different S_n 's, characterizing different r-process paths [7,8]. In our approach, the weighing of the individual r-components is naturally given by the β -decay half-lives of the three waiting-point nuclei $^{80}\text{Zn}_{50}$, $^{130}\text{Cd}_{82}$ and $^{195}\text{Tm}_{126}$ which represent the (main) progenitors of the stable isobars ^{80}Se , ^{130}Te , ^{195}Pt situated at the top of the respective $N_{r,\odot}$ peaks. That this approach has, indeed, a nearly one-to-one mapping to 'realistic' astrophysical environments has been discussed in some detail in [9,16].

In Fig. 5, we show global $N_{r,\odot}$ -fits from a superposition of sixteen components for the two versions of the ETFSI nuclear mass model (ETFSI-1 [46] and ETFSI-Q [47]). In both cases, identical conditions for the stellar parameters were used [10,11]. As is indicated by the dashed fit-curve, when using the original ETFSI-1, apart from pronounced $A \simeq 115$ and $A \simeq 175$ abundance troughs, too little r-process material is observed in the whole region beyond the $A \simeq 130$ peak. These r-abundance deficiencies have been interpreted to arise from an overestimation of the $N=82$ and $N=126$ shell strengths below $^{132}\text{Sn}_{82}$ and $^{208}\text{Pb}_{126}$, respectively. As shown in the previous Sect., first experimental signatures of shell quenching are now, indeed, observed for $N=82$. This strongly justifies our further application of 'quenched' mass models in astrophysical calculations, like the spherical HFB/SkP or the deformed ETFSI-Q. The full curve in Fig. 5 shows the result of multicomponent fit with the latter mass model. When compared to the $N_{r,\odot}$ -fit obtained with ETFSI-1, a considerable improvement of the overall fit is observed. In particular the prominent abundance

troughs in the $A \simeq 115$ and 175 regions are eliminated to a large extent.

Figure 5. Global r-abundance fits for the ETFSI-1 mass model [46] with pronounced shell structure and the ETFSI-Q formula [47] with quenched shell gaps. For discussions, see text and [10,11].

Hence, a 'quenched' mass model for r-abundance calculations beyond $A \simeq 150$ seems to be highly recommended, in particular if predictions for the $A \geq 200$ mass region are anticipated. Of special interest in this context is the good agreement for the region between ^{203}Tl and ^{209}Bi with the recent $N_{r,\odot}$ evaluation of [49]. For ^{209}Bi , for example, a nearly pure r-process origin of this isotope is thus indicated, which confirms that only a minor contribution is of s-origin. As a consequence, there is no further need for the so-called *strong s-process* component, which had been introduced initially to account for the Pb and Bi abundances.

This improvement with the ETFSI-Q masses should also make extrapolations up to the progenitors of the long-lived actinides ^{232}Th and $^{235,238}\text{U}$ more reliable, in particular since they are now for the first time based on an internally consistent, modern nuclear-physics input. Pfeiffer et al. [10] have shown that, only when using nuclear masses which correctly describe the entire *isotopic* $N_{r,\odot}$ pattern, consistent values for the Galactic age of 10-14 Gyr could be obtained. Recently, as a second r-observable *elemental* abundances between Ba and Th, U have been determined in several ultra-metal-poor, neutron-capture-rich halo stars, among them CS 22892-052 [50]. In Fig. 6, these values are compared to the solar r-element distribution and to our ETFSI-Q predictions [10,11], after adjustment to the solar metallicity. The excellent agreement clearly indicates, that the heavy elements in this star are of pure r-process origin. With the measured Th abundance and our calculated initial abundance, a 'decay age' of 13.0 ± 4.6 Gyr [51] for CS 22892-052 can be deduced. This value overlaps with recent Galactic ages on the young side (see, e.g. [52]). Finally, the excellent agreement between the r-element abundances of this first-generation star and the global $N_{r,\odot}$ pattern, which represents a summation over the whole Galactic evolution, indicates that there is probably a *unique* scenario for the r-process (at least for $A > 130$). In the meantime confirmed by further observations [51,53], this result seems to validate our site-independent approach of deducing astrophysical constraints on r-process conditions from fitting r-process

observables, and thus strengthens once again the importance of future nuclear-structure investigations towards the neutron drip-line.

Figure 6. Elemental r-abundances calculated with ETFSI-Q are compared to the respective $N_{r,\odot}$ values (filled circles). Superimposed are measured abundances (filled squares) from the metal-poor halo star CS 22892-052 [50], which were scaled in $\log \epsilon$ to the solar rare-earth values.

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REFERENCES

1. Burbidge, E.M. et al., *Rev. Mod. Phys.* **29**, 547 (1957).
2. Lund, E. et al., *Phys. Scr.* **34**, 614 (1986).
3. Gill, R.L. et al., *Phys. Rev. Lett.* **56**, 1874 (1986).
4. Kratz, K.-L. et al., *Z. Phys.* **A325**, 489 (1986).
5. Kratz, K.-L. et al., *Z. Phys.* **A340**, 419 (1991).
6. Kratz, K.-L., *Rev. Mod. Astronomy* **1**, 184 (1988).
7. Kratz, K.-L. et al., *Ap. J.* **402**, 216 (1993).
8. Thielemann, F.-K. et al., *Nucl. Phys.* **A570**, 329c (1994).
9. Chen, B. et al., *Phys. Lett.* **B355**, 37 (1995).
10. Pfeiffer, B. et al., *Z. Phys.* **A357**, 235 (1997).
11. Kratz, K.-L. et al., *Nucl. Phys.* **A630**, 352c (1998).
12. "Nuclear Structure of the Zirconium Region", *Res. Rep. in Phys.*, Springer, ISBN 0-387-50120-7 (1988).
13. "Nuclei Far From Stability / Atomic Masses and Fundamental Constants 1992", *Inst. of Phys. Conf. Ser.* **132**, IOP, ISBN 0-7503-0262-3 (1993).
14. "Exotic Nuclei and Atomic Masses 1995", *ENAM95*, Edition Frontieres, ISBN 2-86332-186-2 (1995).

15. Takahashi, K. et al., *Astron. Astrophys.* **286**, 857 (1994).
16. Freiburghaus, C. et al., *Nucl. Phys.* **A621**, 405c (1997); and *Ap. J.*, in print.
17. Ameil, F. et al., *Eur. Phys. J.* **A1**, 275 (1998).
18. Franchoo, S. et al., Contrib. PE3 to *ENAM98*; and *Phys. Rev. Lett.*, in print.
19. Wöhr, A. et al., Contrib. C11 to *ENAM98*; and *Phys. Rev. Lett.*, in print.
20. Grzywacz, R. et al., Contrib. C7 to *ENAM98*; and *Phys. Rev. Lett.* **81**, 766 (1998).
21. Schoedder, S. et al., *Z. Phys.* **A352**, 237 (1995).
22. Mehren, T. et al., *Phys. Rev. Lett.* **77**, 458 (1996).
23. Lhersonneau, G. et al., *Eur. Phys. J.* **A1**, 285 (1998).
24. Kurpeta, J. et al., Contrib. PE10 to *ENAM98*; and *Eur. Phys. J.* **A2**, 241 (1998).
25. Hoff, P. et al., *Phys. Rev. Lett.* **77**, 1020 (1996).
26. Sanchez-Vega, M. et al., *Phys. Rev. Lett.* **80**, 5504 (1998).
27. Fogelberg, B. et al., Contrib. PC18, PC30 and PE11 to *ENAM98*.
28. Stone, N.J. et al., *Phys. Rev. Lett.* **78**, 820 (1997).
29. Zhang, C.T. et al., *Z. Phys.* **A358**, 9 (1997).
30. Fedoseyev, V.N. et al., *Z. Phys.* **A353**, 9 (1995).
31. Kautzsch, T. et al., *Phys. Rev.* **C54**, 2811 (1996).
32. Kratz, K.-L. et al., in: "Fission and Properties of Neutron-Rich Nuclei", Sanibel Island, Nov. 1997, World Scientific, in print.
33. Rauscher, T. et al., *Phys. Rev.* **C57**, 2031 (1998).
34. Ragnarsson, I. and Sheline, R.K., *Phys. Scr.* **29**, 385 (1984).
35. Dobaczewski, J. et al., *Phys. Rev. Lett.* **72**, 981 (1994).
36. Pfeiffer, B. et al., *Acta Physica Polonica* **B27**, 475 (1996).
37. Erdmann, N. et al., *Appl. Phys.* **B66**, 431 (1998).
38. Mishin, V.I. et al., *Nucl. Instr. and Meth.* **B73**, 550 (1993).
39. Jading, Y. et al., *Nucl. Instr. and Meth.* **B126**, 76 (1997).
40. Sebastian, V. et al., Contrib. PA15 to *ENAM98*.
41. Zamfir, N.V. et al., *Phys. Rev.* **C51**, 98 (1995).
42. Kautzsch, T., PhD Thesis, Univ. Mainz; and to be published.
43. Möller, P. et al., *At. Data Nucl. Data Tables* **59**, 185 (1995); and **66**, 131 (1997).
44. Kratz, K.-L., in: "Nuclei in the Cosmos III", *AIP Conf. Proc.* **327**, 113 (1995).
45. Möller, P. and Randrup, J., *Nucl. Phys.* **A514**, 1 (1990).
46. Aboussir, Y. et al., *At. Data Nucl. Data Tables* **61**, 127 (1995).
47. Pearson, J.M. et al., *Phys. Lett.* **B397**, 455 (1996).
48. Audi, G. et al., *Nucl. Phys.* **A624**, 1 (1997).
49. Beer, H. et al., *Ap. J.* **474**, 843 (1997).
50. Sneden, C. et al., *Ap. J.* **467**, 819 (1996).
51. Cowan, J.J. et al., *Ap. J.*, in print.
52. Salaris, M. and Weiss, A., *Astron. Astrophys.* **327**, 107 (1997).
53. McWilliam, A. et al., *Astron. J.* **109**, 2757 (1995).