Eur. Phys. J. A **13**, 1–4 (2002)

THE EUROPEAN PHYSICAL JOURNAL A



# High-spin states in neutron-rich nuclei explored with deep-inelastic HI reactions

R. Broda

H. Niewodniczański Institute of Nuclear Physics, Kraków, Poland

Received: 1 May 2001 / Revised version: 25 June 2001

**Abstract.** The use of deep-inelastic heavy-ion reactions for the spectroscopy of neutron-rich nuclei is discussed. Conclusions from the $N/Z$ equilibration process studies are outlined and examples of spectroscopic results obtained for the neutron-rich *spdf* shell nuclei, $N = 82$ isotones and nuclei from the $^{208}$Pb region are reviewed.

**PACS.** 25.70.Lm Strongly damped collisions – 27.40.+z $39 \leq A \leq 58$ – 27.60.+j $90 \leq A \leq 149$ – 27.80.+w $190 \leq A \leq 219$

## 1 Introduction

Increasing prospects for radioactive-ion beam facilities becoming fully operational within the next few years opens new chances for extending the nuclear-structure studies into new regions of the nuclide chart. Already presently available beams of light unstable nuclei contributed with many impressive findings in nuclei located far from the beta stability valley; obviously new interesting results will be presented at this conference. In the hitherto poorly studied neutron-rich region such perspectives seem to be particularly attractive. At this stage it might be useful to discuss some of the present possibilities to investigate the neutron-rich nuclei with the available beams of stable nuclei.

Since nearly a decade we are successfully using the deep-inelastic heavy-ion reactions for spectroscopic studies of nuclei located at the neutron-rich edge of the beta stability valley and beyond (*e.g.*, [1–6]). The high-quality gamma coincidence data obtained in thick-target experiments performed with available large arrays of germanium detectors allow to achieve selectivity which is satisfactory to identify structures of many previously unknown nuclei. Apart from the direct interest in the structure of each specific nucleus which can be accessed in such studies, few points should be stressed to view this research activity as a useful entry to future studies with radioactive beams. First of all it seems to be an economical approach to learn, whatever can be learned in much simpler experiments than those involving beams of unstable nuclei. Second, the detailed information on the structure of neutron-rich nuclei accessible with stable beams should be very useful in planning and controlling the dedicated experiments with radioactive beams, which will usually aim at much more exotic regions. Third, the experience gained in employing deep-inelastic reactions might be essential for future use of such reactions in experiments with radioactive beams. Whereas in the region of light nuclei the prospects for significant progress is obvious, it is not clear at present how to use radioactive beams for the study of neutron-rich heavy nuclei. It seems likely that similar binary reactions will have to be used in spectroscopy of species with large neutron excess.

## 2 The N/Z equilibration process

In deep-inelastic heavy-ion reactions the exchange of nucleons between the two colliding nuclei is driven by a strong tendency to equalize the $N/Z$ ratio. Even the neutron-rich light collision partner has usually much smaller $N/Z$ ratio than the heavy one and readily accepts additional neutrons or gives away protons in mass transfer taking place during the violent nuclear contact. Although this phenomenon was observed and well studied since early years of heavy-ion physics [7], the attained knowledge was not satisfactory for practical use of such reactions in spectroscopic investigations. In particular, detailed predictions of production yields, or expected spin population, were hardly available to plan such experiments. Therefore, after few initial successful spectroscopic applications, we undertook a more systematic study of these deep-inelastic reaction features, which predominantly define their usefulness for the spectroscopy. The better understanding of the $N/Z$ equilibration process was one important aim to optimize the choice of colliding systems for the study of specific neutron-rich nuclei and to clarify limitations of this technique. The power of the gamma coincidence analysis as supplementary tool yielding information on nuclear reactions was demonstrated in the study of the $^{54}$Fe + $^{106}$Cd system [8]. We applied the same technique in the analysis of three other colliding systems, which were selected to study the $N/Z$ equilibration process at collision energies 10 to 15% above the Coulomb barrier. The $^{58}$Ni and $^{64}$Ni beams of 350 MeV energy bombarding the $^{208}$Pb target sampled cases, which differ substantially in initial $N/Z$ ratios. The other $^{64}\mathrm{Ni} + {}^{130}\mathrm{Te}$ neutron-rich combination was selected to include different mass asymmetry and the presence of strong fusion evaporation and fusion-fission channels as compared to the $^{64}\mathrm{Ni} + {}^{208}\mathrm{Pb}$ system. In all three cases the experimental reconstruction of nearly complete primary product distributions, involving also reliable control of the secondary evaporation process, gave the basis for the consideration of $N/Z$ equilibration process. Here, we shall only summarize our final conclusions of this study, referring to much more detailed description presented in our earlier reports [9,10]. At relatively small-mass transfer (up to about 10 nucleons) taking place between the two colliding nuclei, the most probable $N/Z$ ratios of both final fragments rapidly change towards the equilibration value, when the number of transferred nucleons increases. However, at larger-mass transfers the $N/Z$ ratios saturate at values, which are rather far from reaching full $N/Z$ equilibration. As naturally expected, the complete $N/Z$ equilibration values was observed for the fusion-fission products, arising only in the $^{64}\mathrm{Ni} + {}^{130}\mathrm{Te}$ reactions. From the quantitative comparison of experimental results with calculations based on the minimization of the potential energy of two touching spheres, we concluded that the dynamical deformation of colliding nuclei, in time of their nuclear contact, is responsible for the observed incompleteness of the $N/Z$ equilibration. This feature unfortunately sets up a serious limitation on the range of neutron-rich nuclei, which can be accessed in deep-inelastic reactions for spectroscopic study. Consequently, in our experiments we concentrated on investigation of nuclei which are located rather close to the neutron-rich edge of the beta stability valley, but cannot be reached in standard fusion evaporation reactions. In the following, I shall present few examples of nuclei with previously unknown yrast structures, which could be studied by deep-inelastic heavy-ion reactions in simple thick-target gamma coincidence experiments.

## 3 Nuclei from the spdf shells

Exploration of the nuclear structure of neutron-rich nuclei around $N = 20$ revealed interesting phenomena. The Na and Mg isotopes located in this region turned out to be much more bound than predicted by shell model calculations. Moreover, the first $2^+$ state of $^{32}$Mg was found to lie at very low energy compared to other even-even $N = 20$ isotones [11] and the $B(E2)$ value indicated large deformation of $\beta = 0.51$ [12]. These anomalies could be understood within the large-scale shell model calculations, which reproduced the lowering of the $f_{7/2}$ intruder neutron orbital in Ne, Na, Mg neutron-rich isotopes. Experimental conditions for spectroscopic studies in this "island of inversion" region are very demanding, since the nuclei in question are extremely hard to access. Here, particular hopes rely on the progress of experiments with radioactive-beam facilities. Nevertheless, any effort to move with spectroscopic study towards the "island" is important and rewarding; even single new states located by experiment may lead to severe constraints on theoretical shell model calculations. Some of these exotic nuclei were investigated using a technique of intermediate-energy Coulomb excitation of radioactive beams. Energies of the $2^+$ states in $^{40,42}$S and $^{44,46}$Ar [13] were determined with accuracy of about 20 keV and also the $B(E2)$ values were measured. Similar study was performed using relativistic radioactive ion beams taking advantage of larger cross-sections for Coulomb excitation at these energies [14]. The use of deep-inelastic heavy-ion reactions allows to reach some nuclei located in the neutron-rich region of *spdf* shells and early examples of such study were presented already in 1994 [15]. The advantage of using such reactions in connection with simple thick-target gamma coincidence technique is usually good statistics of the collected data and possibility to reach higher-spin states. However it has to be clearly pointed that only states involving lifetimes or feeding times longer than the stopping time of reaction products can be observed; the Doppler broadening of transitions depopulating short-lived states prevents completely their detection. Another complication is related to difficulties encountered in identification of unknown structures, which has to be done by complex analysis of gamma cross-coincidences with transitions occurring in the known accompanying fragment present in the reaction exit channel. Even inaccurate values of crucial gamma transition energies coming from experiments with radioactive beams are very helpful in the identification procedure. We used these early identifications of radioactive-beam experiments [13] to search for the structure of the neutron-rich Ar and S isotopes. In experiments performed with the EUROBALL at the INFN Legnaro we bombarded the $^{48}$Ca target backed by the thick $^{208}$Pb layer with the $^{48}$Ca beam of 140 MeV energy. The analysis of triple gamma coincidences allowed to identify the lowest-lying transitions from the $^{44}$Ar and $^{46}$Ar isotopes, which appeared in cross-coincidences with the known transitions of correspondingly $^{52}$Ti and $^{50}$Ti partner product nuclei. The more detailed analysis established also higher-lying states in the $^{44}$Ar isotope as shown in fig. 1, which includes also S isotopes with our results indicated for the $^{40}$S isotope. One should emphasize that in these light nuclei future prospects to extend the experimental information to more exotic neutron-rich isotopes is particularly bound to progress with radioactive-beam experiments.

## 4 Neutron-rich N = 82 isotones

Much of experimental and theoretical effort was devoted to study the $N = 82$ isotones. The physical question was focussed on finding out to what extent the low-energy yrast structures can be understood by considering simple two-body interactions of valence protons moving in the

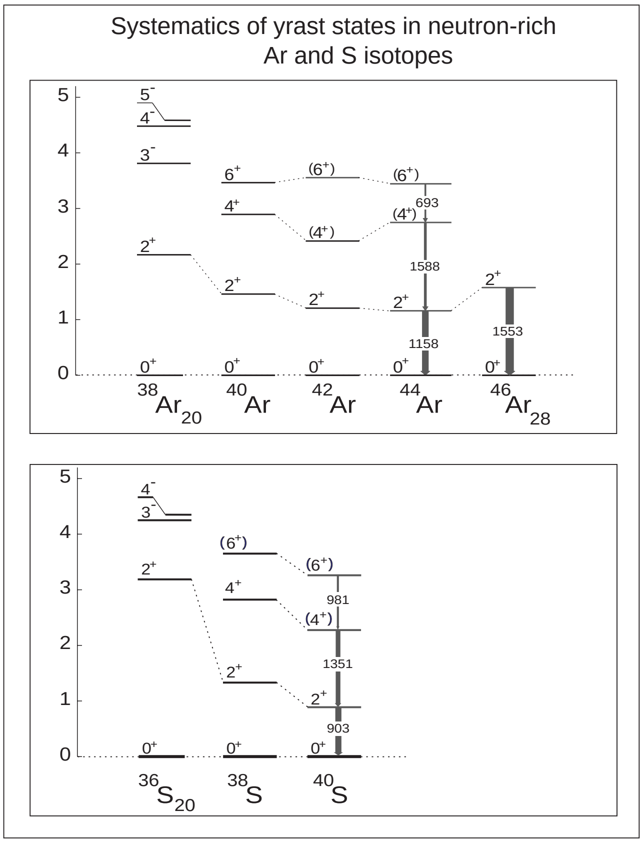


**Fig. 1.** Systematics of yrast excitations in neutron-rich even Ar and S isotopes.

mean field produced by the inert $^{132}$Sn core. The experimental results were obtained using large variety of techniques. They extend through the whole series of $N = 82$ isotones —from the very neutron-rich $^{132}$Sn core to the very neutron-deficient $^{154}$Hf nucleus. The large part of higher $Z$ isotone study was performed using standard fusion evaporation reactions, but the neutron-rich isotones could be accessed only in the spontaneous-fission spectroscopy. The detailed structure revealed recently for the two- and three-valence proton $^{134}$Te and $^{135}$I isotopes [16, 17] provided basic knowledge of empirical two-body effective interactions used in the shell model calculations. In a comprehensive shell model analysis including the whole series of $N = 82$ isotones these empirical two-body interactions were continuously refined to reproduce levels observed in subsequent experiments. T. Wildenthal constructed the full Hamiltonian [18] which described consistently all observed yrast structures. Further refinement was made by J. Blomqvist who used the new experimental input from the study of the $^{134}$Te, $^{135}$I and $^{136}$Xe [19] isotopes. One of the most important outputs of this effort was the detailed quantitative prediction of the yrast structure of the five-valence proton isotope $^{137}$Cs, which at the time was experimentally completely unknown. The $^{137}$Cs cannot be reached in any fusion evaporation process; also the extremely small production yield in the spontaneous fission contributed to difficulties in the experimental study of this isotope. Here, the employment of deep-inelastic reaction presented a good chance to demonstrate the usefulness of the discussed spectroscopic technique to overcome such difficulties. The data from the GAMMASPHERE experiment $^{136}$Xe + $^{232}$Th were used to search for the unknown yrast structure of $^{137}$Cs, which should be produced in processes involving transfer of one proton to the $^{136}$Xe projectile. Results of this analysis revealed a very transparent scheme of yrast levels extending to the 5.5 MeV excitation energy and maximum spin value of 31/2 and uniquely identified with the $^{137}$Cs isotope [20]. Except for the two levels which could be attributed to the neutron core excitations, all other states reflect the one-to-one correspondence with yrast levels calculated theoretically by considering only the coupling of five-valence protons. The spectacular quantitative agreement of the observed experimental excitation energies with the ones calculated prior to experiment gave clear-cut suggestions for spin parity assignments and demonstrated the predictive power of the semi-empirical shell model approach. It is now followed by more fundamental theoretical attempts to calculate such structures starting from free nucleon-nucleon interactions. A detailed information on the neutron-rich $N = 82$ isotones study may be found in refs. [16, 17, 20, 21].

## 5 The $^{208}$Pb region — two-proton hole $^{206}$Hg nucleus

The use of deep-inelastic heavy-ion collisions in gamma spectroscopy investigations gave access to yrast structures of many nuclei located in the doubly magic $^{208}$Pb region. The anticipated purity of many high-spin states populated in these nuclei makes them a particularly attractive object of investigation and provides good testing ground for the shell model analysis. Already in the early stage of our thick-target gamma coincidence experiments, several new high-spin states could be observed in the $^{208}$Pb itself. They were uniquely identified with the simple particle-hole excitations extending to the 6.744 MeV $14^-$ state, notably the highest-spin coupling of the $j_{15/2}$ neutron particle with the $i_{13/2}$ neutron hole [3]. The continued experimental effort extended the level scheme of the $^{208}$Pb to much higher-spin states including the observation of the 28 ns isomeric state of yet unknown structure [22]. Similarly the completely new high-spin state structures of the $^{207}$Pb [2, 22], $^{209}$Pb [23] and $^{210}$Pb [24] isotopes could be experimentally established reaching previously inaccessible ranges of spin values. The study has shown a particular role of the octupole vibrations of the $^{208}$Pb core in building up yrast structures by coupling such collective mode with various single-particle excitations [25]. This investigations include also more complex nuclei located in the $^{208}$Pb region and the case of $^{211}$Po [26] might be an example of potential lying in the analysis of the high-quality data collected with large gamma detector arrays in experiments involving non-fusing heavy-ion systems.

It seems to be appropriate to close this brief review with our most recent result concerning the yrast structure

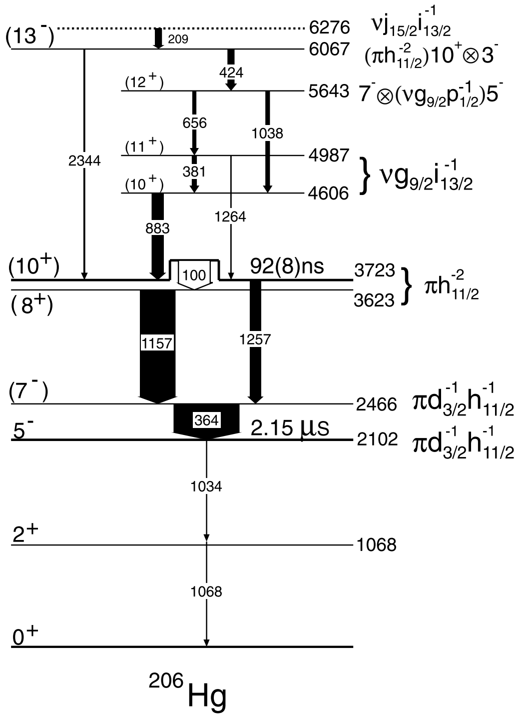


**Fig. 2.** Yrast level scheme of the two-proton hole $^{206}$Hg nucleus as identified in [27]. The suggested level structures are indicated.

of the two-proton hole $^{206}$Hg nucleus. This particularly attractive result is now nearly ready for publication [27] and I am very happy that with consent of authors I may include it into my presentation at this conference. The long-lived 2.2 $\mu$s isomeric state $5^-$ $(h_{11/2}s_{1/2})$ was for long time the highest-spin state known in the $^{206}$Hg nucleus. In many of our experiments involving the $^{208}$Pb target we observed the population of this isomer, yet in spite of efforts we were not able to identify any structure above it. The search was mainly aimed at the identification of the $10^+$ isomeric state, which is expected to have a particularly high-purity structure arising from the coupling of the two $h_{11/2}$ proton holes. The break-through came from the analysis of the new data obtained in the $^{208}$Pb + $^{238}$U experiment performed with the GAMMASPHERE and the $^{208}$Pb beam from the ATLAS accelerator at the Argonne NL. The 1.6 $\mu$s beam pulsing repetition time gave a satisfactory time space to analyse delayed coincidences across the $^{206}$Hg $5^-$ isomer and to identify crucial transitions preceding the isomer as shown in fig. 2. The three most intense of them were clearly found as following the decay of the higher-lying isomer and established the position of the expected $10^+$ isomer. Whereas only traces of a strongly converted 100 keV $E2$ gamma isomeric branch could be observed, its intensity was easily extracted and together with the measured half-life value of 92(8) ns allowed to determine the effective charge of $1.60(7)e$ for the $h_{11/2}$ proton hole. The subsequent analysis of delayed coincidences with transitions following the $10^+$ isomer identified several new states located above the isomer as shown in fig. 2. The straightforward interpretation of these new levels is indicated in fig. 2. It is worthwhile to pay attention to the suggested $13^-$ state at 6.067 MeV which could be yet another example of the octupole vibrational state; this time coupled to the two aligned $h_{11/2}$ proton holes.

## 6 Conclusions

In conclusion of this review I would like to indicate the ongoing progress in using deep-inelastic heavy-ion reactions for spectroscopy of nuclei located close to the neutron-rich edge of the beta stability valley in various parts of the nuclide chart. The further application of the presented technique, which employs stable nuclei as beams and targets, should be helpful in the preparation of dedicated experiments with radioactive beams aiming at more exotic regions of neutron excess.

The author expresses his gratitude to all collaborators who contributed to the results presented in this review. This work has been supported by the Polish Scientific Committee under grant no. 2P03B-150-10.

## References

1. R. Broda *et al.*, Phys. Rev. Lett. **68**, 1671 (1992).
2. M. Schramm *et al.*, Z. Phys. A **344**, 121 (1992).
3. M. Schramm *et al.*, Z .Phys. A **344**, 363 (1993).
4. T. Pawlat *et al.*, Nucl. Phys. A **574**, 623 (1994).
5. B. Fornal *et al.*, Phys. Rev. C **55**, 762 (1997).
6. R. Broda *et al.*, Phys. Rev. Lett. **74**, 868 (1995).
7. D.A. Bromley, *Treatise of Heavy Ion Science* (Plenum, New York, 1984).
8. R. Broda *et al.*, Phys. Rev. C **49**, (1994). R575
9. W. Krolas, Ph.D. Thesis, INP Report, No. 1738/PL, Krakow, 1996.
10. R. Broda *et al.*, Heavy Ion Phys. **7**, 71 (1998).
11. D. Guillemaud-Mueller *et al.*, Nucl. Phys. A **426**, 37 (1984).
12. T. Motobayashi *et al.*, Phys. Lett. B **346**, 9 (1995).
13. H. Scheit *et al.*, Phys. Rev. Lett. **77**, 3967 (1996).
14. S. Wan *et al.*, Eur. Phys. J. A **6**, 167 (1999).
15. B. Fornal *et al.*, Phys. Rev. C **49**, 2413 (1994).
16. J.P. Omtvedt *et al.*, Phys. Rev. Lett. **75**, 3090 (1995).
17. C.T. Zhang *et al.*, Phys. Rev. Lett. **77**, 3743 (1996).
18. B.H. Wildenthal, in *Understanding the Variety of Nuclear Excitations*, edited by A. Covello (World Scientific, Singapore, 1991).
19. J. Blomqvist, Acta Phys. Pol. B **30**, 697 (1999).
20. R. Broda *et al.*, Phys. Rev. C **59**, 3071 (1999).
21. P.J. Daly *et al.*, Phys. Rev. C **59**, 3066 (1999).
22. R. Broda *et al.*, *Proceedings of the International Conference on Nuclear Structure at the Limits, Argonne 1996*, ANL/PHY-97/1 (1997) p. 276.
23. M. Rejmund *et al.*, Eur. Phys. J. A **1**, 261 (1998).
24. M. Rejmund *et al.*, Z. Phys. A **359**, 243 (1997).
25. M. Rejmund *et al.*, Eur. Phys. J. A **8**, 161 (2000).
26. B. Fornal *et al.*, Eur. Phys. J. A **1**, 355 (1998).
27. B. Fornal *et al.*, Phys Rev. Lett. **87**, 212501 (2001).