Quadrupole collectivity of neutron-rich nuclei around ^{132}Sn

Th. Kröll[*], T. Behrens[*], R. Krücken[*], V. Bildstein[*], T. Faestermann[*], R. Gernhäuser[*], M. Mahgoub[*], P. Maierbeck[*], M. Münch[*], W. Weinzierl[*], F. Ames[†], D. Habs[†], O. Kester[†], R. Lutter[†], T. Morgan[†], M. Pasini[†], K. Rudolph[†], P. Thirolf[†], J. Diriken[**], M. Huyse[**], O. Ivanov[**], P. Mayet[**], N. Patronis[**], I. Stefanescu[**], J. Van de Walle[**], P. Van Duppen[**], O. Niedermaier[‡], H. Scheit[‡], D. Schwalm[‡], J. Eberth[§], F. Finke[§], D. Martin[§], P. Reiter[§], A. Scherillo[§], M. Seidlitz[§], N. Warr[§], D. Weisshaar[§], J. Iwanicki[¶], P. Butler[‖,††], J. Cederkäll[‖], E. Clément[‖], P. Delahaye[‖], L. M. Fraile[‖], G. Georgiev[‖], U. Köster[‖], T. Sieber[‖], D. Voulot[‖], F. Wenander[‖], S. Franchoo[‡‡], A. Hurst[††], A. Ekström[§§], P. E. Kent[¶¶], K.-H. Speidel[***], J. Leske[***,†††], S. Schielke[***], A. Jungclaus[‡‡‡], V. Modamio[‡‡‡], J. Walker[‡‡‡], L. Coquard[†††], M. Pantea[†††], N. Pietralla[†††], T. Davinson[§§§], S. Nardelli[¶¶¶] and the REX-ISOLDE and MINIBALL collaborations

[*] *Physik-Department E12, Technische Universität München, Garching, Germany*
[†] *Fakultät für Physik, Ludwig-Maximilians-Universität München, Garching, Germany*
[**] *Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, Belgium*
[‡] *Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
[§] *Institut für Kernphysik, Universität zu Köln, Germany*
[¶] *Środowiskowe Laboratorium Ciężkich Jonów, Uniwersytet Warszawski, Poland*
[‖] *CERN, Genève, Switzerland*
[††] *Oliver Lodge Laboratory, University of Liverpool, United Kingdom*
[‡‡] *Institut de Physique Nucléaire, Orsay, France*
[§§] *Fysiska Institutionen, Lunds Universitet, Sweden*
[¶¶] *Department of Physics, University of York, United Kingdom*
[***] *Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, Germany*
[†††] *Institut für Kernphysik, Technische Universität Darmstadt, Germany*
[‡‡‡] *Departamento de Física Teórica, Universidad Autónoma de Madrid, Spain*
[§§§] *Department of Physics and Astronomy, University of Edinburgh, United Kingdom*
[¶¶¶] *INFN and Dipartimento di Fisica, Università di Camerino, Italy*

Abstract. We report on the "safe" Coulomb excitation of neutron-rich Cd, Xe, and Ba isotopes in the vicinity of the doubly-magic nucleus ^{132}Sn. The radioactive nuclei have been produced by ISOLDE at CERN and postaccelerated by the REX-ISOLDE facility. The γ-decay of excited states has been detected by the MINIBALL array. The presented preliminary results for the $B(E2)$ values are consistent with expectations from phenomenological systematics and will be compared with theoretical calculations.

Keywords: Coulomb excitation, gamma spectroscopy, neutron-rich nuclei
PACS: 25.70.De, 21.10.Re, 27.60.+j

CP1012, *Frontiers in Nuclear Structure, Astrophysics, and Reactions: FINUSTAR 2*
edited by P. Demetriou, R. Julin, and S. V. Harissopulos

MOTIVATION

The explanation of the magic numbers for nuclei in the valley of stability was one of the milestones in the understanding of nuclear structure. Important interest nowadays is the question if they persist or will be altered going away from the valley of stability because the residual interactions responsible for their existence may change. We report here on Coulomb excitation studies of nuclei around ^{132}Sn, the heaviest doubly-magic nucleus off stability which is accessible for experiments so far.

In our naive understanding of collective states large $B(E2)$ are accompanied with low excitation energies. The product between the $B(E2; 0^+_{gs} \rightarrow 2^+_1)$ value and the excitation energy $E(2^+_1)$ in even-even nuclei has a smooth behaviour near to the valley of stability and can be described by a simple phenomenological formula [1]. A significantly improved description could be obtained by multiplying Raman's version of Grodzins' formula [2] with an isospin dependent modification [3].

An indication for a deviation from this simple picture came some years ago from $B(E2)$ values for neutron-rich Sn and Te nuclei in the vicinity of ^{132}Sn [4] which were lower than expectations from systematics. As theoretical explanation a reduced neutron pairing above $N = 82$ has been proposed. QRPA calculations were able to reproduce the small $B(E2)$ value for ^{136}Te [5]. Following this argumentation collectivity in these very neutron-rich nuclei is built up mainly by neutrons resulting in low $B(E2)$ values. Other theoretical calculations using the Monte Carlo Shell Model [6] or the shell model with a realistic interaction based on the CD Bonn NN-potential [7] reproduced the low $B(E2)$ value only partially. Meanwhile, a new Coulomb excitation measurement indicates 30% larger $B(E2)$ values [8]. Furthermore, a lifetime measurement for the first 2^+ state in ^{136}Te using the ultrafast timing technique even results in a 50% larger $B(E2)$ value [9].

Aiming to extend such investigations, we studied neutron-rich Cd, Xe, and Ba isotopes at the REX-ISOLDE facility at CERN.

EXPERIMENTAL METHOD

The radioactive nuclei have been produced at the ISOLDE facility at CERN by the 1.4 GeV proton beam from the PS Booster impinging on a UC_x target. For some isotopes neutron induced fission has been applied using a neutron converter target to reduce the proton-rich isobaric contaminants. For each beam the target and the ion source have been optimised for elemental selectivity. The extracted ions were mass separated, cooled and bunched in the Penning trap REX-TRAP, and sent to an EBIS for charge breeding. Eventually, the energy was boosted to around 2.85 MeV/u by the REX-LINAC [10]. The REX-ISOLDE facility will be upgraded to HIE-ISOLDE in the next years [11].

We employed γ-spectroscopy following "safe" Coulomb excitation of the radioactive beams. The γ-rays deexciting the populated states were detected by the highly efficient MINIBALL spectrometer, consisting of 8 triple clusters of six-fold segmented HPGe detectors equipped with fully digital electronics [12], in coincidence with the scattered particles. Since most ISOL beams, in our case all but the Xe beams, are not pure beams, several methods to determine the beam composition have been applied.

The $B(E2)$ values of radioactive beams are determined relative to those of the target

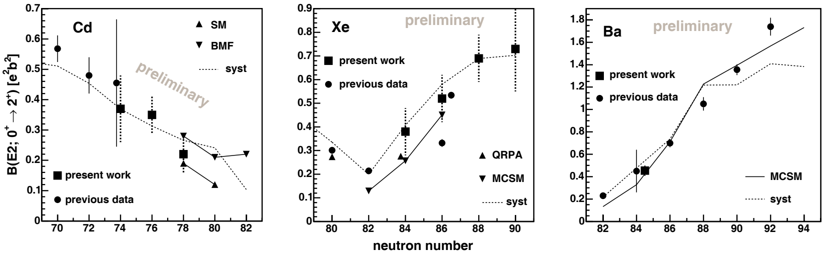

FIGURE 1. $B(E2)$ values for Cd (left), Xe (middle) and Ba (right) isotopes in comparison with previous data, phenomenological systematics, and theoretical models. For details and references see text.

whose electromagnetic properties are well known. For the beam nuclei the $B(E2)$ values have been varied until the cross sections, calculated with an extended version of the CLX code [13], agree with the experimental values.

More details of Coulomb excitation experiments at REX-ISOLDE with MINIBALL can be found also in further contributions to this conference [14].

PRELIMINARY RESULTS FOR $B(E2)$ VALUES

The analysis is still in progress and we will present here only preliminary results [15].

For the Cd isotopic chain, the last known $B(E2)$ value is for ^{122}Cd, however only within an error of 50% [16] (note that a wrong value is given in Raman's compilation [2]). We determined the $B(E2)$ values for ^{122,124,126}Cd. As it can be seen in Fig. 1 (left), the values agree well with the simple systematical formula.

Recent interest in this region comes from nuclear astrophysics, as the nuclei below ^{132}Sn are so-called waiting point nuclei of the r-process. From the study of the β-decay of ^{130}Cd it was deduced that its binding energy is lower than expected from mass models [17]. This has been interpreted as signature of a quenching of the $N = 82$ shell gap. With this assumption the $A \approx 130$ peak in the r-process abundances can be described better. On the other hand, in a recent study of the decay of the 8^- isomer a good agreement with the $(\nu g_{9/2})^{-2}$ description and, hence, no evidence for a shell quenching was found [18]. A beyond mean field (BMF) approach with projection on particle number and angular momentum predicts for the neutron-rich Cd isotopes rather a prolate deformation than a spherical shape. In Fig. 1 (left), the theoretical predictions are included. The shell model (SM) using a realistic interaction derived from the CD Bonn NN-potential without assuming a shell quenching predicts a steep decrease of the $B(E2)$ values approaching $N = 82$ [19]. Clearly larger $B(E2)$ values are predicted by the BMF approach [18].

For the Xe isotopes previously no $B(E2)$ had been measured above $N = 82$, except the two contradicting values for ^{140}Xe [2, 20]. We determined $B(E2)$ values for ^{138,140,142,144}Xe. Our preliminary values, as shown in Fig. 1 (middle), clearly follow the systematical formula. For ^{140}Xe, our result supports the larger value from literature [20]. The experimental values are compared with predictions from QRPA calculations [5] as well as from the Monte Carlo Shell Model (MCSM) [6]. Both models give lower $B(E2)$ values for ^{138}Xe, however still within the preliminary error.

Aiming to extend this studies to more deformed nuclei, we started with the ^{140,142}Ba isotopes in a first beam time in July 2007. Within the $N = 84$ isotonic chain, for ^{140}Ba a $B(E2)$ value has been measured previously but with a large error which we will improve. Attempts to measure also the very exotic ^{148,150}Ba failed because of technical problems. Our preliminary $B(E2)$ value for ^{140}Ba, previous experimental data [2, 9], the systematical formula, and predictions from the MCSM [6] are shown in Fig. 1 (right).

g-factor measurements

A more direct probe for an increased neutron content in the wave functions are g-factors. The relevant neutrons occupy the $f_{7/2}$ orbital and their contribution has a negative sign resulting in a small, maybe even negative, g-factor different from the collective Z/A value [21]. As Te beams are not yet available with sufficient intensities, we studied the g-factors of the first 2^+ states in the ^{138}Xe and ^{140}Ba $N = 84$ isotones.

For the ^{138}Xe, we performed an experiment applying the transient field method to be sensitive to the sign of the g-factor [21]. The data are still under analysis [22]. The Ba will be studied applying recoil-in-vacuum method [23]. The data set for ^{142}Ba, for which the g-factor of the 2_1^+ state is known, will serve as a calibration. This analysis will be applied also to the Xe data sets.

Transfer reactions

With Coulomb excitation mainly the collective properties of nuclei are studied. Nevertheless the obtained results are very well described by modern theoretical calculations, there is an increasing interest to investigate also the single particle structure of nuclei by nucleon transfer reactions. At REX-ISOLDE, one- or two-neutron transfer reactions in inverse kinematics are planned using deuterium or tritium targets.

The emitted protons are detected by a new array of position sensitive Si detectors which covers a large angular range to determine the angular distributions accurately. The set-up fits inside MINIBALL to detect efficiently γ-rays in coincidence.

As a first experiment in autumn 2007, the shore of the "island of inversion" will be studied with the reaction d(^{30}Mg,^{31}Mg)p [24]. Also studies of neutron-rich Ca isotopes and nuclei in the region around ^{68}Ni [25] are planned already.

Summary and outlook

We have presented the preliminary $B(E2)$ values for neutron-rich nuclei in the vicinity of the doubly-magic nucleus ^{132}Sn. All results are well within the expectations from simple phenomenological systematics. However, predictions based on nuclear models differ significantly and our final results will allow in most cases to distinguish between them [15]. Further information will come from the determination of g-factors.

We will extend our studies to the nucleus ^{128}Cd to evidence the predicted prolate deformation for neutron-rich Cd isotopes. The systematic investigations will be continued towards more deformed nuclei by the study neutron-rich Ba isotopes where also octupole degrees of freedom are expected to become important.

Such investigations will allow deeper insights into the isospin dependence of the quadrupole collectivity and the underlying physics of their phenomenological systematics in this region of high interest for both nuclear structure and nuclear astrophysics.

ACKNOWLEDGMENTS

This work is supported by the German BMBF under grant No. 06MT238, by the MLL, by the EU through EURONS (contract No. 506065), and by the DFG cluster of excellence Origin and Structure of the Universe (URL: www.universe-cluster.de). REX-ISOLDE and MINIBALL are supported by the German BMBF, the Belgian FWO-Vlaanderen and IAP, the U.K. EPRSC, and the EU, as well as the ISOLDE collaboration.

REFERENCES

1. L. Grodzins, Phys. Lett. 2, 88 (1962).
2. S. Raman et al., Atomic Data and Nuclear Data Tables 78, 1 (2001).
3. D. Habs, R. Krücken et al., CERN Proposal INTC-P-156 (2002).
4. D. C. Radford et al., Phys. Rev. Lett. 88, 222501 (2002); Proc. of INPC2004 and ENAM'04.
5. J. Terasaki et al., Phys. Rev. C 66, 054313 (2002).
6. N. Shimizu et al., Phys. Rev. Lett. 86, 1171 (2001), Phys. Rev. C 70, 054313 (2004), and J. Phys. Conf. Ser. 49, 178 (2006).
7. A. Covello et al., Proc. of RNB7 (2006).
8. C. Baktash et al., MAFF Workshop (2005).
9. H. Mach et al., contribution to this conference; L. M. Fraile et al., Proc. of INPC2007.
10. O. Kester et al., Nucl. Instr. and Meth. B 204, 20 (2003).
11. K. Riisager et al., contribution to this conference.
12. J. Eberth et al., Prog. Part. Nucl. Phys. 46, 389 (2001).
13. H. Ower, computer program CLX, not published.
14. G. Georgiev et al., J. Van de Walle et al., and A. Ekström et al., contributions to this conference.
15. T. Behrens, PhD Thesis (TU München, 2007); to be published.
16. N. V. Zamfir et al., Phys. Rev. C 51, 98 (1995).
17. I. Dillmann et al., Phys. Rev. Lett. 91, 162503 (2003).
18. A. Jungclaus et al., Annual NUSTAR Meeting, GSI (2007); private communication.
19. A. Scherillo et al., Phys. Rev C 70, 054318 (2004).
20. A, Lindroth et al., Phys. Rev. Lett. 82, 4783 (1999).
21. K.-H. Speidel et al., CERN Proposal INTC-P-166 (2003).
22. J. Leske et al., Annual Spring Meeting of DPG, Giessen (2007).
23. N. Stone et al., Phys. Rev. Lett. 94, 192501 (2005).
24. V. Bildstein et al., ISOLDE Workshop 2007; PhD thesis (TU München).
25. N. Patronis et al., contribution to this conference.