Advances in experimental and theoretical studies of heavy, very heavy and super-heavy nuclei

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SCIENTIFIC ISSUE

At present, the upgrade or construction of several new devices for prompt gamma-spectroscopy is underway in Europe, such as the AGATA array, the VAMOS Gas-Filled separator at GANIL as well as SAGE and MARA at the University of Jyväskylä. These will present unprecedented means to study collective states throughout the chart of nuclei and will allow for the detailed study of shape coexistence, K isomerism, the evolution of moments of inertia with angular momentum, and the role of intruder states for these phenomena.

In order to maximize the impact of the upcoming experimental campaigns in view of the limited beam-time and manpower available they should be coordinated in order to avoid overlap between experiments, and it also appears advantageous to have the opinion of theoreticians which observables, states and nuclei can be expected to be the most revealing for the thorough understanding of the nuclear structure phenomena at play and the improvement of theoretical models.

Eight years ago, two of us (CT and MB) organized an ESNT workshop on the "Spectroscopy of transactinide nuclei" that brought together experimentalists and theoreticians to discuss and imagine the breakthroughs that can be expected to be realized with the state-of-the-art techniques of the time. While that earlier workshop focused on the complementarity of the different techniques available to study one specific region of the nuclear chart, we propose this time a workshop on how the specific technique of prompt gamma-ray spectroscopy can be used to advance our understanding of nuclei in different regions of the chart of nuclei that have in common that they present a complicated pattern of excited collective states.

Among these, the region of very heavy elements (VHEs) and super-heavy elements (SHEs) is probably still the area of the nuclear chart where physicists have to face the most complex and extreme conjunctions of experimental and theoretical problems. Despite the tremendous experimental difficulties, impressive progresses have been reported during the past few years:

in 2012 the elements 114 and 116 have been approved and baptized Flerovium and Livermorium respectively, GSI has confirmed this year element 117 first reported by Dubna in 2010; the prompt spectroscopy of ^{256}Rf has been performed at the University of Jyväskylä; prompt spectroscopy of high-K states has been reported for ^{252}No; results for the measurement of the fission barrier of ^{254}No have been reported last year, etc. However, the actinide and transactinide region is still poorly known. Still, a lot of problems still need to be solved on both experimental and theoretical sides.

The study of some other regions of the nuclear chart faces the same problems as the one of the SHE region. Actually, the same experimental techniques are used and continually improved to track the most rare and exotic isotopes. The VHE/SHE region, neutron-deficient region and the region "north-east" of ^{100}Sn have in common low production cross-sections, high background contamination, and the presence of alpha emitters that require the use of the RDT technique. It turns out that similar problems are also faced on the theoretical side in these exotic regions. We therefore propose to discuss in the same workshop advances in these three mass regions.

- VHE, SHE region. This region is one of the most challenging ones of the entire nuclear chart. While an island of stability has been predicted about 50 years ago, still the precise nature and location of the SHE spherical shell gap, if there is one at all, is unknown. Among the questions we can address, let us mention: What can we learn from the study of Z=100-106 (deformed) nuclei concerning the heaviest (spherical) nuclei? In that respect, which nuclei and/or states are the most relevant: even-even, proton-odd, neutron-odd, K-isomers, etc.? Spectroscopy of high-K states reveals the interplay between different phenomena: deformation, rotation, pair-breaking, octupole correlations, band crossing. How to combine all of these aspects into a single consistent picture?

- The neutron-deficient lead region is the area of the nuclear chart where shape coexistence is the most abundant. Experimentally, this region is very challenging since the isotopes are very far from the beta-line of stability. However, transition rates have recently been measured for very exotic Pt, Hg, Pb, Po isotopes, thereby providing insight into the nature of low-lying exotic states. In particular, they suggest that low-lying states often mix configurations with different shapes. While all self-consistent mean-field models do predict multiple shape coexistence for nuclei in this region, they all often fail to predict the correct energy difference between the various structures, even when including, in one way or the other, correlations beyond the mean field. One notorious example are the Hg isotopes around ^{182}Hg that usually are predicted to have prolate ground states, in contradiction with experimental evidence. Which are the missing ingredients of the models? Will improved effective interactions resolve the problem, or does the description of correlations has to be pushed much further? Which data will help to discriminate between both? How are the microscopic effects connected to the Z=82 shell closure?

- Alpha-emitters North-East of ^{100}Sn. The region around ^{100}Sn is of utmost interest, since this nucleus is at the drip line, with two closed shells and N=Z. It is a benchmark to investigate the states near the Fermi surface and how their wave functions reflect single-particle motion. Discrepancies between the eigenvalues of the single-particle Hamiltonian of spherical self-consistent mean-field calculations and empirical single-particle energies have stimulated several attempts to improve effective interactions through the introduction of tensor forces. There is, however, no guarantee that one describes the other, such that a much more sophisticated modeling is necessary to correctly describe these nuclei.

The Xe and Te light isotopes display several interesting collective features. Less neutron deficient Xe isotopes (A>114) are the only cases of shape coexistence in the vicinity of the Z=50 shell closure. Coexistence of prolate, oblate configurations and octupole and gamma bands are suggested. Approaching the N=Z line close to the dripline, an increase of collectivity has been observed in the Xe isotopes, in contradiction with the vicinity of the N=50 shell closure. To explain this unexpected behavior, theoretical model suggest the influence of the T=0, J>0 coupling. This particular n-p pairing remains poorly known. At the drip line, new radioactive decay modes are predicted. How to describe shape coexistence just above Z=50? From where does the onset of collectivity in the light Xe isotope come from? Does cluster radioactivity exist in these nuclei?

GOALS OF THE WORKSHOP

In 2007, an ENST workshop was organized on "Spectroscopy of transactinide nuclei" with the goal to gather theoreticians and experimentalists to discuss the prospects of this field of research. Eight years after, the idea is to discuss recent results and future experiments with AGATA&VAMOS@GANIL and other state of the art facilities such as RITU@JYFL. We propose to have overviews of experimental (theoretical) techniques with an emphasis on observables in a direct link with theory (experiment), in a realistic way. We expect that new ideas will emerge from the workshop on both experimental and technical sides even if very challenging (also on both sides). It goes without saying that experimental (theoretical) presentations should be pedagogical enough such that theoreticians (experimentalists) can follow. Perspectives on a longer term should be discussed, e.g. with future (radioactive beam) facilities.

PROGRAM

(Preliminary) Schedule

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<tr><th></th><th>Monday 16th</th><th>Tuesday 17th</th><th>Wednesday 18th</th><th>Thuesday 19th</th></tr>
<tr><td>09:15 - 10:15</td><td rowspan="2">Coffee & welcome</td><td>C. Scholey</td><td>B. Birkenbach</td><td>T. Niksic</td></tr>
<tr><td>10:15 - 10:30</td><td colspan="3">Coffee</td></tr>
<tr><td>10:30 - 11:30</td><td>M. Bender</td><td>J. Pakarinen</td><td>C. Fransen</td><td>G. Henning</td></tr>
<tr><td>11:30 - 12:30</td><td>M. Sandzelius</td><td>B. Cederwall</td><td>Th. Duguet</td><td>N. Pillet</td></tr>
<tr><td colspan="5">Lunch</td></tr>
<tr><td>14:00 - 15:00</td><td>B. Sulignano</td><td>A. Poves</td><td>E. Clement</td><td rowspan="4">General discussion: Future experimental and theoretical trends</td></tr>
<tr><td>15:00 - 15:15</td><td colspan="3">Coffee</td></tr>
<tr><td>15:15 - 16:15</td><td>A. Afanasjev</td><td>P. Van Isacker</td><td>L. Robledo</td></tr>
<tr><td>16:15 - 17:15</td><td>J. Piot</td><td>P.-H. Heenen</td><td>J. Ljungvall</td></tr>
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19:30 : Dinner in Orsay

List of contributions

- M. Bender (CENBG Bordeaux, France)

  Mean-field-based tools for the description of excited states of heavy nuclei

  This introductory presentation will give an overview over the directions of ongoing developments that aim at improving the mean-field-based modelling of ground- and excited states in medium-heavy and heavy nuclei and the probabilities of gamma transitions between them. Points to be addressed will be the breaking of symmetries on the mean-field level, their subsequent restoration, the necessity of configuration mixing to describe coexisting shapes, the choice of effective interactions, and the limitations imposed by numerical cost on today's computers, which calls for educated choices made for the degrees of freedom explicitly treated in the calculations (although there is no guarantee that nature behaves as we expect) and/or suitable approximation schemes (although there is no guarantee that these always catch all of the relevant physics).

- M. Sandzelius (University of Jyväskylä, Finland)

Overview of recent and future experiments of transfermium nuclei in the deformed region around N=152

In the Very Heavy Element (VHE) and Super Heavy Element (SHE) region there exist a rather clear disagreement between the prediction of the positioning of the next spherical shell gap. Different models predict either Z=124 or Z=120 as the next possible spherical shell closure above Z=82. However, spectroscopic information for these nuclei is as of today non-existent, and probably will remain so for the foreseeable future due to minuscule production cross-sections. In the VHE transfermium region, for $100<Z<106$ and $N\approx152$, nuclei can readily be produced in sufficient quantity to extract spectroscopic information (with in-beam and delayed decay spectroscopy). Moreover, these nuclei are relatively strongly deformed in their ground state. This deformation causes intruder states emanating from the SHE region (above Z=124) to come down in energy forming orbitals at the Fermi surface in some transfermiun nuclei. Therefore it is of vital importance to map the single-particle states near the Fermi surface in order to test the success and validity of nuclear models.

In particular, odd-mass nuclei provide the opportunity to test single-particle spectra predicted by theory. Thus, the study of transfermium nuclei around the deformed region of N=152 and $Z>100$ can be viewed as a stepping stone towards superheavy nuclei and the nebulous island of stability. In the transfermium region there exists the possibility to probe the orbitals that are relevant in these very exotic nuclei with significantly higher N and Z numbers, which are otherwise inaccessible with today's technology.

Great progress has recently been made with the use of efficient detector set-ups. The data, although scarce, have shed light on theoretical weaknesses. As an example there exists now a rather clear disagreement between the predictions of the shell positioning obtained from all existing effective interactions/energy density functionals (predicting N=150 and Z=98,104 as a sub-shell closure) and experiment (which seem to predict N=152 and Z=100 as subshell closure).

This talk will give an overview of some of the spectroscopic information recently gathered in the $100<Z<106$ region around the deformed region of N=152, and also present some future experiments planned at JYFL. Also, some experimental challenges and limitations to what we can measure will be presented.

- B. Sulignano (CEA Saclay, France)

Investigation of high-K states in transfermium nuclei

Study of K isomerism in the transfermium region around the deformed shells at N=152, Z=102, and N=162, Z=108 provide important information on the structure of heavy nuclei. The structure of such nuclei is of particular importance since the single particle levels involved are relevant for the next shell closure expected to form the region of the shell stabilized super heavy elements at proton numbers 114, 120, or 126 and neutron number 184. K isomers, in particular, could be an ideal tool for the synthesis and study of these isotopes due to enhanced spontaneous fission lifetimes [1], which could result in higher alpha to spontaneous fission branching ratios and longer half-life.

Experimental examples are the recently studied of two quasi-particle K isomers in ^{250,256}Fm, ^{250,252,254}No [2], and ^{270}Ds [3]. Nuclei in this region, are produced with cross sections ranging from several nb up to μb, which are high enough for a detailed decay study. In this contribution I will give an overview of the K isomeric states found in transfermium nuclei and compare them with the last theoretical calculation such as the new triaxial self-consistent Hartree-Fock-Bogoliubov calculations using the D1S force and breaking time-reversal as well as z-signature symmetries.

S. Hofmann *et al.*, Eur. Phys. J. A 10, 5 (2001). 292 (2007).

B. Sulignano *et al.*, Physical Review C 86, 044318 (2012).

D. Ackermann doi:10.1016/j.nuclphysa.2015.09.002

- A. Afanasjev. (Mississippi State University, USA)

From actinides to superheavy nuclei:benchmarking theory and addressing theoretical uncertainties

The questions of the existence limits and the properties of shell-stabilized superheavy nuclei have been a driving force behind experimental and theoretical efforts to study such nuclei. Unfortunately, theoretical predictions for superheavy nuclei differ considerably. In such a situation, heavy actinides and known superheavy nuclei play a role of testing ground for many theoretical approaches. The systematic study of these nuclei allows to define the sources of theoretical uncertainties, to quantify these uncertainties and possibly estimate their propagation to unknown superheavy nuclei. The present status of our understanding of heavy and superheavy nuclei in covariant density functional theory (CDFT) will be discussed. I will concentrate on several aspects which define the shell structure, physical observables and stability of heavy and superheavy nuclei. These are single-particle degrees of freedom [1-4], pairing interactions [5], rotational excitations [5,6] and fission barriers [2,7,8]. I will also revisit the question of shell structure of superheavy nuclei based on the covariant energy density functionals, the global performance of which has recently been established [8]. Global studies of superheavy nuclei including deformation effects performed with these functionals point towards the importance of the neutron shell gap at N = 184 [4]; the role of this gap is frequently overlooked in the CDFT studies restricted to spherical shape. Theoretical uncertainties in the description of different physical observables will also be discussed.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Number DE-SC0013037.

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[4] S. E. Agbemava, A. V. Afanasjev, T. Nakatsukasa and P. Ring, submitted to Phys. Rev. C

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[7] H. Abusara and A. V. Afanasjev and P. Ring, Phys. Rev. C82, 044303 (2010).

[8] H. Abusara and A. V. Afanasjev and P. Ring, Phys. Rev. C85, 024314 (2012).

[9] S. E. Agbemava, A. V. Afanasjev, D. Ray and P. Ring, Phys. Rev. C 89, 054320 (2014).

- J. Piot (GANIL, Caen, France)

Investigation on the collectivity in the transfermium region

The study of collective motion in the region of transfermium nuclei brings information on the single particle involved in their structure. The power of the JUROGAM and JUROGAM2 arrays associated to digital electronics allowed experimentalists to access nuclei with nano barn level cross-section up to high spin. This talk will concentrate on the cases of transfermium nuclei in gamma-ray spectroscopy at JYFL with perspectives using AGATA with the VAMOS Gas-filled mode at GANIL.

P.T. Greenlees et al. Phys.Rev.Lett. 109, 012501 (2012)

J. Piot et al. Phys.Rev. C 85, 041301 (2012)

- C. Scholey (University of Jyväskylä, Finland)

Selective techniques for Gamma-ray Spectroscopy, using gas-filled separators

The art of gamma-ray spectroscopy relies on selective techniques, which allow gamma-rays to be associated with their nucleus of origin. Various tagging techniques have been developed and exploited at University of Jyvässklyä, for almost 20 years and are the workhorse for in-beam and focal plane γ-ray spectroscopy of neutron deficient and heavy elements. The advances in both the technique and in instrumentation have allowed the study of very exotic nuclei, down the the 10 nano-barn cross-section level. What this means in different mass regions and what the possibilities and limitations are shall be discussed using specific examples of heavy N=Z nuclei travelling up the proton dripline towards Pb.

- J. Pakarinen (University of Jyväskylä, Finland)

In-beam spectroscopy in the neutron-deficient Pb region

One of the goals of modern nuclear physics research is to understand the origin of coexisting nuclear shapes, exotic excitations and their relation to the fundamental interactions between the nuclear constituents. Despite of huge amount of both theoretical and experimental efforts, many open questions remain [1 and references therein]. In order to verify and understand these subjects in more detail, complementary approaches are needed. For example, the experimental program carried out at JYFL has included in-beam electron and gamma-ray spectroscopy and lifetime measurements. The post-accelerated radioactive ion beams available at REX-ISOLDE, CERN, have allowed the Coulomb excitation experiments to be performed using the MINIBALL gamma-ray spectrometer [3]. This talk will give an overview of shape coexistence studies carried out JYFL and ISOLDE. The advantages of these different techniques will be discussed and an insight into few selected cases will be given.

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[3] N. Warr et al., Eur. Phys. J. A 49, 40 (2013).

- B. Cederwall (KTH Royal Institute of Technology, Stockholm, Sweden)

  Probing quadrupole and octupole collectivity, superallowed alpha decays and cluster radioactivity in the N~Z, Te-Ce region with the next generation recoil-decay tagging experiments.

- A. Poves (Universidad Autónoma de Madrid, Spain)

  Shape Coexistence: A Shell Model View

  I shall discuss the meaning of the ”nuclear shape” in the laboratory frame proper to the Spherical Shell Model, and the algebraic models that make its foundations. Shape coexistence, shape mixing and shape entanglement will be illustrated with relevant physics cases.

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  [3] Elliott J P 1956 Proc. R. Soc. London, Ser. A 245 128, ibid. 1958, 562.

  [4] Heyde K and Wood J 2011 Rev. Mod. Phys. 83 1467.

  [5] Arima A, Harvey M and Shimizu K 1969 Phys. Lett. B 30 517. Hecht K and Adler A 1969 Nucl. Phys. A 137 129.

  [6] Zuker A P, Poves A, Nowacki F and Lenzi S M 2015 Phys. Rev. C 92 024320.

- P. Van Isacker (GANIL, Caen, France)

  Aligned neutron-proton pairs in N=Z nuclei

- P.-H. Heenen (Université libre de Bruxelles, Belgium)

  Effects of the introduction of correlations beyond a mean-field approach in the description of heavy nuclei

- B. Birkenbach (IKP Köln, Germany)

  Spectroscopy of heavy nuclei after multinucleon-transfer reactions

- C. Fransen (IKP Köln, Germany)

  Exploring heavy nuclei from lifetime measurements of excited states

  Absolute transition strengths are fundamental observables for the understanding of nuclear structure and can be directly determined from level lifetimes. We give an overview about lifetime experiments performed by our group. Although our mostly applied method is the recoil distance Doppler-shift (RDDS) technique [1] we also used fast timing (see, e.g., [2]) and the Doppler-shift attenuation method (DSAM). Our recent projects focus on investigations of heavy neutron deficient nuclei with state-of-the-art gamma-ray spectrometers including recoil identification. The aim is to learn about phenomena like shape coexistence including configuration mixing [3,4] and the shape phase transition from vibrators to axial rotors with special respect to nuclei at the critical point of this transition [5]. Further, an identification of candidates of so-called mixed-symmetry states in the vicinity of ^{208}Pb from a recent DSAM measurement will be shown.

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[2] M.Rudigier et al., Phys.Rev. C 91, 044301 (2015)

[3] L.P.Gaffney et al., Phys.Rev.C 89, 024307 (2014); Erratum Phys.Rev.C 89, 059905 (2014)

[4] K.A.Gladnishki, P.Petkov, A.Dewald, C.Fransen, M.Hackstein, J.Jolie, Th.Pissulla, W.Rother, K.O.Zell, Nucl.Phys. A877, 19 (2012)

[5] A.Dewald et al., Journal of Physics G 31, S1427 (2005)

- T. Duguet (CEA Saclay France, KU Leuven Belgium and MSU USA)

  Non-observable nature of the nuclear shell structure: meaning, illustrations and consequences

  The concept of single-nucleon shells dates back to the early days of contemporary nuclear physics and constitutes the basic pillar of our understanding of nuclear structure. However, effective single-particle energies (ESPEs) are intrinsically theoretical quantities that "run" with the non-observable resolution scale s employed in the calculation (while true observables do not). A formal discussion will be provided to explain the difference between observable and non-observable quantities and the reasons why ESPEs, i.e. the shell structure, belongs to the latter category. State-of-the-art ab-initio calculations based on chiral two- and three-nucleon interactions will be employed to illustrate the situation. This will be done by comparing the behavior of observables and non-observable ESPEs under (quasi) unitary similarity renormalization group transformations of the Hamiltonian parameterized by the resolution scale s. The non-observable nature of the nuclear shell structure, i.e. the fact that it constitutes an intrinsically theoretical notion with no counterpart in the empirical world, must eventually be recognized and assimilated. Given that ESPEs do constitute a useful tool to interpret the behaviour of many-body observables in terms of simpler theoretical ingredients, the ultimate goal of the study is to specify the terms, i.e. the exact sense and conditions, in which this interpretation can be conducted meaningfully.

- E. Clément (GANIL, Caen, France)

  Quadrupole collectivity: A probe for nuclear structure studies around ^{100}Sn.

- L. Robledo (Universidad Autónoma de Madrid, Spain)

  Octupole correlations in Heavy and SuperHeavy nuclei

Permanent octupole deformation seems to be a rare property of the nuclear ground state only present in a few actinide and rare-earch nuclei. However, dynamical correlations are pervasive and could play an important role in the understanding of nuclear dynamics. In this talk I will discuss the theoretical tools used to describe such degree of freedom as well as the physical effects associated to it.

L. M. Robledo and G. F. Bertsch; Phys. Rev. C 84, 054302

L. M. Robledo and G. F. Bertsch; Phys. Rev. C 86, 054306

L M Robledo; Journal of Physics G: Nuclear and Particle Physics, 42, 055109 (2015)

- J. Ljungvall (CSNSM Orsay, France)

  Lifetime measurements of excited states in (super)-heavy nuclei

  In the last few decades spectroscopic information on heavy and super-heavy nuclei have become more and more abundant. A large number of excited states have been mapped out using in-beam prompt spectroscopy and decay spectroscopy.

  There are however very few, if any, direct measurements of transition probabilities of non-isomeric states using prompt spectroscopy of the heaviest nuclei. To perform such measurements is however extremely difficult and I will, after having introduced the experimental techniques, discuss the challenges and what, if any, means we have to overcome the difficulties.

- T. Niksic (University of Zagreb, Croatia)

  Relativistic Nuclear Energy Density Functionals: applications in the region of heavy nuclei

  Relativistic energy density functionals (REDF) have become a standard tool for nuclear structure calculations, providing a complete and accurate, global description of nuclear ground states and collective excitations. Semi-empirical functionals have been adjusted to bulk properties of finite nuclei, and applied to studies of arbitrarily heavy nuclei and exotic nuclei far from stability. REDF-based structure models have also been developed that go beyond the static mean-field approximation, and include collective correlations related to the restoration of broken symmetries and to fluctuations of collective variables. These models are employed in analyses of structure phenomena related to shell evolution, including detailed predictions of excitation spectra and electromagnetic transition rates. The seminar will highlight some of the recent applications of the REDF based theoretical models based in the region of heavy and superheavy nuclei.

V. Prassa, B.-N. Lu, T. Niksic, D. Ackermann, D. Vretenar, "High-K isomers in transactinide nuclei close to N=162", Phys. Rev. C 91, 034324 (2015).

J. Zhao, B.-N. Lu, D. Vretenar, E.-G. Zhao, S.-G. Zhou, "Multidimensionally constrained relativistic mean-field study of triple-humped barriers in actinides", Phys. Rev. C 91, 014321 (2015).

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V. Prassa, T. Niksic, D. Vretenar, "Structure of transactinide nuclei with relativistic energy density functionals", Phys. Rev. C 88, 044324 (2013).

- G. Henning (IPHC Strasbourg, France)

  Stability of V&SHE: fission barrier measurements

  Abstract: The fission barrier is a key parameter in the stability of very and super heavy elements. Without the stabilizing shell effects the spontaneous fission lifetime of isotopes such as ^{254}No would be many orders of magnitude shorter than observed [1]. Recently, the fission barrier height of ^{254}No has been measured to be Bf=6.6 +/- 0.9 MeV at spin 0 hbar, implying a 5 MeV strong shell effect stabilization [2,3]. The method of such measurement will be presented, along with a discussion of the results and their interpretation.

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- N. Pillet (CEA Bruyères le Châtel, France)

  Two- and four-quasiparticle states in Z = 94-112 nuclei with HFB/D1S calculation

Various references:

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L. M. Robledo and G. F. Bertsch, "Global systematics of octupole correlations in even-even nuclei", Phys. Rev. C 84 (2011) 054302.

L. M. Robledo and P. A. Butler, "Quadrupole-octupole coupling in the light actinides", Phys. rev. C 88 (2013) 051302(R).

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