Istros

Isospin, Structure, Reaction and Energy of Symmetry 2023

5th. Edition

14.–19. May 2023

2023

Book of Abstracts

of the Istros 2023
International Conference

Contents

Research opportunities with laser spectroscopy of radioactive molecules

Michail Athanasakis[1]
[1] *CERN, Switzerland*

The electronic structure of molecules that contain radioactive nuclei can be highly sensitive to a number of nuclear observables of interest, such as the typically studied nuclear magnetic dipole and electric quadrupole moments, but also the symmetry-violating nuclear Schiff, anapole, and magnetic quadrupole moments.
Precision experiments based on heavy and polar radioactive diatomic molecules have been proposed as potentially the most sensitive probes to pin down the level of parity and time-reversal violation in the Universe. Beyond the fundamental interest, such experiments on radioactive molecules can also provide new nuclear structure information, test the power of quantum chemistry, and elucidate the astrophysical origin of radionuclides.
In this talk, an overview of the research opportunities for fundamental, nuclear, chemical, and astrophysical studies with radioactive molecules will be given. A summary of recent activities on the production and study of radioactive molecules at CERN-ISOLDE will be followed.

Probing proton emitters using the MARA separator

Kalle Auranen[1], P. Siwach[2], P. Arumugam[3], A.D. Briscoe[1], L.S. Ferreira[4], T. Grahn[1], P.T. Greenlees[1], A. Herzáň[5], A. Illana[1], D.T. Joss[6], H. Joukainen[1], R. Julin[1], H. Jutila[1], M. Leino[1], J. Louko[1], M. Luoma[1], E. Maglione[4], J. Ojala[1], R.D. Page[6], J. Pakarinen[1], P. Rahkila[1], J. Romero[1,6], P. Ruotsalainen[1], M. Sandzelius[1], J. Sarén[1], A. Tolosa-Delgado[1], J. Uusitalo[1], G. Zimba[1]

[1] *Accelerator Laboratory, Department of Physics University of Jyväskylä, FI-40014 Jyväskylä, Finland*
[2] *Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[3] *Department of Physics, Indian Institute of Technology Roorkee, Roorkee 247667, India*
[4] *Centro de Física e Engenharia de Materiais Avançados CeFEMA, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, P1049-001 Lisbon, Portugal*
[5] *Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*
[6] *Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*

Using the fusion-evaporation reaction ^{96}Ru(^{58}Ni,$p4n$)^{149}Lu and the MARA vacuum-mode recoil separator we have identified a new proton-emitting isotope ^{149}Lu. The measured decay Q-value of 1920(20) keV is the highest measured for a ground-state proton decay, and it naturally leads to the shortest *directly* measured half-life of 450^{+170}_{-100} ns for a ground-state proton emitter. The decay rate is consistent with $l_p = 5$ emission, suggesting a dominant $\pi h_{11/2}$ component for the wave function of the proton-emitting state. Through non-adiabatic quasiparticle calculations we were able to conclude that ^{149}Lu is the most oblate deformed proton emitter observed to date. In this talk the experimental details and the already published results [1] are discussed. Additionally, we collected a good number of recoil-decay tagged γ rays feeding the also proton decaying ^{147}Tm and ^{147m}Tm. The level schemes extracted from these data are also presented and discussed.

References

[1] K. Auranen *et al.*, Phys. Rev. Lett. **128**, 112501 (2022).

New collective structures in ^{179}Au

Matúš Balogh[1,2], **M. Venhart**[2]
[1] *INFN Laboratori Nazionali di Legnaro, IT-35020 Padova, Italy*
[2] *Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*

The odd-mass Au isotopes offer a broad systematic view of nuclear structure in a region of near-degenerate, multiple coexisting shapes [1]. The most neutron-deficient Au isotopes have been the subject of an extensive program of experimental investigation in the past. In comparison to the heavier Tl and Au isotopes, where multiple shape coexistence has been established [1-4], a rich variety of structures remains to be discovered. Indeed, already it is evident that there are new structures in ^{177}Au [5] and ^{179}Au [6] that have no counterpart in the heavier Au isotopes, as far as current spectroscopy has revealed.
In this contribution, the results from the in-beam γ-ray and isomeric-decay spectroscopy of the extremely neutron-deficient isotope ^{179}Au will be presented. This high-statistics study was performed at the Accelerator Laboratory of the University of Jyväskylä utilizing the JUROGAM II array, the RITU separator and the GREAT focal-plane spectrometer. A previously unknown, high-spin isomeric state with an excitation energy of 1743(17) keV and $T_{1/2} = 2.16(8)$ µs was discovered. Five decay paths were identified, some of them feeding previously unknown non-yrast excited states associated with proton-intruder configuration. No such isomer was previously observed in heavier Au isotopes. Additionally, a new rotational band, associated with the unfavoured signature band of the $1h_{9/2} \oplus 2f_{7/2}$ proton-intruder configuration was revealed.
Calculations based on the particle-plus-triaxial-rotor model [7] were performed to interpret these newly observed structures in ^{179}Au.

References

[1] K. Heyde, J.L. Wood, Rev. Mod. Phys. **83** (2011) 1467.
[2] D. Rupnik *et al.*, Phys. Rev. C **58** (1998) 771.
[3] C.D. Papanicolopulos *et al.*, Zeitschrift für Physik A Atomic Nuclei **330** (1988) 371.
[4] D. Rupnik *et al.*, Phys. Rev. C **51** (1995) 0.
[5] M. Venhart *et al.*, Phys. Rev. C **95** (2017) 061302(R).
[6] M. Venhart *et al.*, Phys. Lett. B **695** (2011) 82.
[7] S.E. Larsson *et al.*, Nuclear Physics A **307** (1978) 189.

Experimental Research Projects on High Spin States and Exotic Shapes in Medium-Heavy Nuclei

Piotr Bednarczyk[1]

[1] *Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*

Super-deformed bands known in some nuclei close to ^{40}Ca can be interpreted in terms of the shell model, cluster approach or mean-field theory. It is expected that the SD bands in this region may be related, through emission of alpha -particles or high-energy photons, to the rapid rotation of hot highly deformed compound nucleus. However, the lack of the high-spin experimental data makes it difficult to conclusively explain the origin of collectivity in these nuclei. On the other hand, the advantage of nuclei of interest is that the deformed low spin members of the collective bands can be studied in detail, including direct measurements of their quadrupole moments, which gives their shape. Furthermore, exotic shape isomers are expected to coexist here with the spherical ground states. The use of the new generation of gamma-ray spectrometers, such as AGATA and PARIS, in combination with particle detectors, will enable investigations of the rotational bands in the full angular momentum range, from the band-heads up to or beyond the band termination. These studies will include the search for possible feeding of the SD bands by alpha particles or high-energy gamma-radiation. Also, the unprecedented sensitivity of these novel instruments will facilitate the quest for structures corresponding to exotic nuclear symmetries.

Search for a light Dark Boson with the New JEDI project

Beyhan Bastin[1] **on the behalf of the New JEDI (Core and Extended) collaboration**
[1]GANIL, Caen, France

Understanding the composition and functioning of our Universe are among the most fundamental and challenging questions in Physics. To date, the intrinsic nature of dark matter remains a mystery. This presentation is about the New JEDI project which aims to study through several nuclear physics experiments a fascinating alternative scenario, such as the existence of an indirect interaction between ordinary matter, well described by the Standard Model, and the Darks Sectors of the Universe via portals (so called Dark Bosons). In other words, does a new fifth force of nature exist?
Our investigation is further motivated by the recent claim of an anomaly observed in the electron-positron pair decays of an excited state in ^{8}Be, during an experiment of the Hungarian ATOMKI group, which may be interpreted as the signature of a hypothetical dark boson (named X17). However, uncertainties linked to the structure of ^{8}Be and new hypotheses to explain the experimental results are currently debated. The ATOMKI group confirmed latter on the existence of this anomaly on other nuclei such as ^{4}He and ^{12}C. The quantum nature of this hypothetical boson is also unclear at the moment. Independent measurements are needed.
For three years now, the collaboration has worked on the construction of a new detection system, named New JEDI. The latter is designed to be versatile in order to make a proposal for a large-scalebroadband experimental program. The project relies on pathfinder experiments conducted at the ARAMIS-SCALP facility (Orsay, France). The commissioning of the New JEDI setup has been completed successfully on June 2021 at a tandetron facility in (Rez, Czech Republic). The first experiment hastaken place in June-July 2022 at the ANDROMEDE facility (Orsay, France). A complementary experiment is foreseen in 2023 at the iThemba LABS laboratory. We plan to develop a long-term research program in the MeV terra incognita energy range at the new SPIRAL2 facility (Caen, France), that will deliver unique high-intensity beams of light, heavy-ions and neutrons in Europe.In the presentation, we will present the overall New JEDI project and provide for a synthesis about the measurements carried out up to now.

Experimental research program in the Tandetron laboratory of the IoP SAS

Monika Bírová[1], Martin Venhart[1], Stanislav Hlaváč[1], Andrej Herzáň[1]

[1] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*

Experimental research program in the Tandetron laboratory of the Institute of Physics of the Slovak Academy of Sciences operates a new accelerator laboratory in Piešťany [1]. It is equipped with an electrostatic accelerator of the Tandetron® type with a terminal voltage of up to 2 MV. In conjunction with the Duoplasmatron ion source, it can deliver light ion beams: protons, deuterons (up to 4 MeV) or alpha beams (up to 6 MeV). Detection of gamma and X-rays is provided by an array of four coaxial HPGe detectors and three $LaBr_3$(Ce) detectors. A fully digital data acquisition system, based on Pixie-16 commercial digitizers, is available. The local group developed a code to correct measured data with an unstable baseline of the detectors [2].
The experimental research program includes, e.g., the study of shape coexistence in the vicinity of the closed proton shell Z = 28. As part of the experiment, it was necessary to construct a goniometer for mounting HPGe detectors. It will allow precise measurements of the angular distribution. This will be essential for the determination of $M1/E2$ mixing ratios for ΔJ = 1 transitions. In Piešťany laboratory, it is possible to have long-running experiments, which is important for study transitions with low intensities.
Plans for the expansion of the equipment, including the construction of the ΔE - E telescope, will be presented. The physical motivation of the experiment together with the current knowledge of shape coexistence in the vicinity of nickel and copper nuclei will be discussed. In particular, the presentation will be focused on the case of the ^{61}Cu isotope and its unknown $M1/E2$ mixing ratio for deexcitation of the first excited level.

References

[1] Nuclear Physics News **33**, 6 (2023).
[2] M. Balogh *et al.*, Nucl. Inst. And Met. Phys. Res. C **1004**, 165368 (2021).

First observation of the radiative decay of ^{229}Th low-lying isomer

Premaditya Chhetri[1], **M. Athanasakis[2]**, **S. Bara[1]**, **K. Beeks[3]**, **A. Claessens[1]**, **G. Correia[2]**, **L. Da Costa Pereira[1]**, **H. De Witte[1]**, **R. Ferrer[1]**, **S. Geldhof[1]**, **N. Hosseini[3]**, **S. Kraemer[1]**, **Y. Kudrayavtsev[1]**, **M. Laatiaoui[4]**, **R. Lica[2]**, **G. Maghiels[1]**, **J. Moens[1]**, **S. Raeder[5]**, **T. Schumm[3]**, **S. Sels[1]**, **P. Thirolf[6]**, **M. Tunhuma[1]**, **P. Van den Bergh[1]**, **P. Van Duppen[1]**, **A. Vantomme[1]**, **R. Villareal[1]**, **U. Wahl[7]**

[1]*KU Leuven, Belgium*
[2]*CERN, Switzerland*
[3]*TU Wein, Austrai*
[4]*HIM Mainz, Germany*
[5]*GSI Datmstadt, Germany*
[6]*LMU Munich, Germany*
[7]*ULisboa, Portugal*

Owing to its very low excitation energy the isomer of thorium-229 has been proposed as a candidate for a possible future frequency standard, a nuclear clock and is expected to outperform the current atomic clocks [1,2]. Currently, the best values of the excitation energy are 8.28(17) eV and 8.10(17) eV [3,4]. These were measured using two different techniques where the population of the isomer was achieved via the α-decay of uranium-229. However, a precise knowledge of the isomer excitation energy is a necessary for the development of an optical clock.
Recently, spectroscopy measurement has been possible using an alternative approach of populating the isomer via the beta decay of actinium-229 [5]. The laser ionized actinium-229 ions produced online at CERN's ISOLDE facility were implanted onto a large bandgap crystal at specific lattice positions. A favourable feeding fraction of the isomer from the beta decay of actinium-229 compared to that via the $\alpha-$decay of uranium-229 and a low beta energy compared to alpha decay leads to a significantly reduced radioluminescence. This allowed us to study the VUV-photons stemming from the radiative decay of the isomer for the first time resulting in a much precise determination of the energy and lifetime of the isomer.
In this contribution, a dedicated setup developed at KU Leuven for the implantation of francium/radium/actinium-229 beam into large-bandgap crystals and the vacuum-ultraviolet spectroscopic study of the emitted photons will be presented.

References

[1] E. Peik *et al.*, Europhys. Lett. **61**, 2 (2003).
[2] C. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012).
[3] B. Seiferle *et al.*, Nature **573**, 243-246 (2019).
[4] T. Sikorsky *et al.*, Phys. Rev. Lett. **125**, 142503 (2020).
[5] M. Verlinde *et al.*, Phys. Rev. C **100**, 024315 (2019).

Highlights from the AGATA campaign at LNL

Franco Galtarossa[1] for the AGATA collaboration
[1] *INFN Sezione di Padova, Padova, Italy*

The γ-ray tracking array AGATA [1] has been installed at the Legnaro National Laboratories (Italy) [2] after 7 years of operation at GANIL (France) [3]. The first experimental campaign started in May 2022, with AGATA coupled to the magnetic mass spectrometer PRISMA and other ancillary detectors, such as Silicon arrays, MCP detectors and scintillators.
In the last year year, 15 experiments have been performed, aiming at the study of nuclear structure and reaction dynamics all along the nuclear chart. A large variety of reaction mechanisms have been employed, such as Coulomb excitation, single and multi-nucleon transfer reactions and fusion-fission reactions with stable beams at energies of 5-10 MeV/u.
In the talk the experimental set-up and some selected highlights from the campaign will be presented, together with future perspectives of AGATA at LNL, where radioactive ion beams from SPES [4] are expected to be delivered in the coming years.

References
[1] S. Akkoyun *et al.*, Nucl. Instrum. Methods Phys. Res. A **668** (2012) 26-58.
[2] J. J. Valiente-Dobón *et al.*, Nucl. Instrum. Methods Phys. Res., A **1049** (2023) 168040.
[3] E. Clément *et al.*, Nucl. Instrum. Methods Phys. Res. A **855** (2017) 1-12.
[4] https://www.lnl.infn.it/en/spes-2/

Shape coexistence in the Ru isotopes

Paul E. Garrett[1,2]
[1] *Department of Physics, University of Guelph, Guelph, ON N1G2W1, Canada*
[2] *Instituut voor Kern- en Stralingsfysica, KU Leuven, Celestijnenlaan 200d, B-3001 Heverlee, Belgium*

The structures of the Ru isotopes in the vicinity of $N = 58$ have been interpreted in a variety of ways. The systematics of the 2_1^+ energies, and the $E(4_1^+)/E(2_1^+)$ energy ratios, have been used to suggest an evolution from a spherical vibrational scheme for the lighter Ru isotopes (^{96,98}Ru) to that of a γ-soft rotor for the heavier ones (^{106,108}Ru) (see, e.g., Refs.[1-5]). They are also in a region where an abundance of examples of shape coexistence exist, located midway between the Sr/Zr isotopes and the Cd/Sn isotopes [6,7]. Shape coexistence has been predicted to occur in some of the Ru isotopes, but previously the only firm experimental evidence has been from the results of detailed Coulomb excitation studies of ^{104}Ru [8,9]. Aside from purely structural interest, the Ru isotopes are parent (^{96}Ru) or daughter (^{100,102}Ru) candidates for searches for the $0\nu\beta\beta$ process. The anti-correlation between the nuclear matrix elements and the change in the deformation between the parent and daughter state [10] implies that knowledge on both ground state and excited state deformations are important if such processes were to yield an observable double-β-decay signal.
We have recently initiated a systematic investigation of the Ru isotopes using a variety of structural probes including β-decay, transfer reactions, (n,γ) capture reactions, and Coulomb excitation. In ^{98}Ru, combining data from a β-decay experiment at iThemba LABS and the ^{100}Ru(p,t) reaction performed at the Maier-Leibnitz Laboratory, a γ-band and 0_2^+ band were identified. Combined with beyond-mean-field calculations using the symmetry conserving configuration mixing (SCCM) framework, the interpretation of the low-lying states in ^{98}Ru was dramatically changed, and shape-coexistence was suggested to be present across the stable Ru isotopes [11]. New results from the Coulomb excitation of ^{102}Ru support this conclusion [12]. The decay scheme of ^{100,102}Ru has also been dramatically extended from very-high-statistics γ-ray spectroscopy following the (n,γ) reaction using the FIPPS facility at the ILL Grenoble. Candidate band structures in ^{100}Ru have been identified using complementary data from the ^{102}Ru(p,t) reaction. This presentation will focus on the new results from our investigations, with the implications on the nuclear structure in the region.

References

[1] J. Stachel *et al.*, Phys. Rev. C **25**, 650 (1982).
[2] I. Stefanescu *et al.*, Nucl. Phys. **A789**, 125 (2007).
[3] A. Giannatiempo *et al.*, Phys. Rev. C **52**, 2969 (1995).
[4] J.L.M. Duarte *et al.*, Phys. Rev. C **57**, 967 (1997).
[5] H. Duckwitz *et al.*, Nucl. Phys. **A903**, 18 (2013).
[6] K. Heyde and J.L. Wood, Rev. Mod. Phys. **83**, 1467 (2011).
[7] P.E. Garrett, M. Zielińska and E. Clément, Prog. Part. Nucl. Phys. **124**, 103931 (2022).
[8] J. Stachel *et al.*, Nucl. Phys. **A383**, 429 (1982).
[9] J. Srebrny *et al.*, Nucl. Phys. **A766**, 25 (2006).
[10] J. Engel and J. Menendez, Rep. Prog. Phys. **80**, 046301 (2017).
[11] P.E. Garrett *et al.*. Phys. Lett. **B809**, 135762 (2020).
[12] P.E. Garrett *et al.*, Phys. Rev. C **106**, 064307 (2022).

Lifetime measurements of neutron-deficient odd-A W and Os nuclei

Tuomas Grahn[1]

[1] *Accelerator Laboratory, Department of Physics University of Jyväskylä, FI-40014 Jyväskylä, Finland*

We have carried out a series of lifetime measurements of excited states in the vicinity of ^{168}Os, where a peculiar feature of $B(E2;4^+ \rightarrow 2^+)/B(E2;2^+ \rightarrow 0^+) < 1$ has been observed [1]. Subsequent measurements have confirmed that this feature can be found in W, Os and Pt nuclei close to N = 92. To date, no sound explanation based on contemporary nuclear models have been found. The transition energies of the ground-state bands suggests that these bands would be collective, and perhaps triaxial. However, the transition probability systematics disagree with the predictions of available collective nuclear models.
In ^{172}Pt, the phase transition has been suggested to be responsible of this feature [2]. Our latest study of ^{163}W [3] has elaborated the role of the odd nucleon and geometric features in description of decrease of collectivity as a function of spin.
The presented Recoil Distance Doppler-Shift measurements have been carried out at University of Jyväskylä using the JUROGAM γ-ray spectrometer. The results of the experiments and their possible interpretations will be discussed.

References

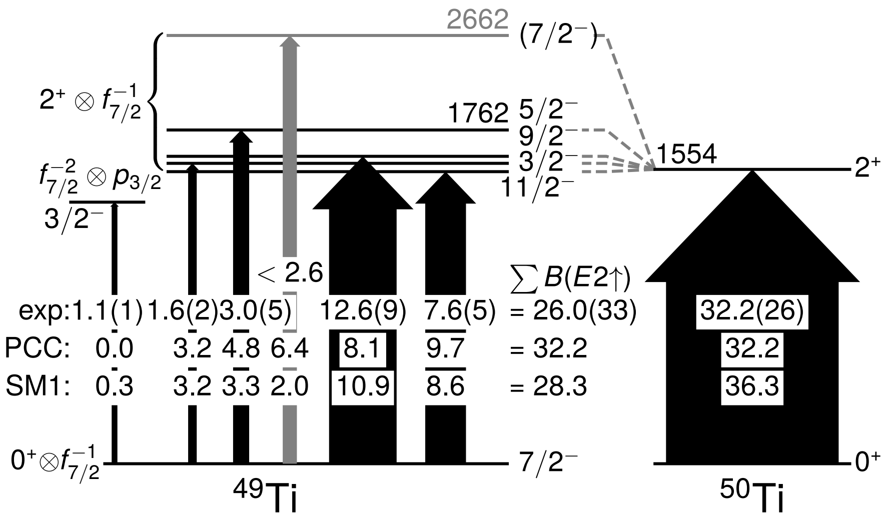
[1] T. Grahn *et al.*, Phys. Rev. C **94**, 044327 (2016)
[2] B. Cederwall *et al.*, Phys. Rev. Lett. **121**, 022502 (2018)
[3] M. C. Lewis *et al.*, Phys. Lett. B, **798**, 134998 (2019)

Suppressed Electric Quadrupole Collectivity in ^{49}Ti Relative to Semi-Magic ^{50}Ti

Timothy J. Gray[1]

[1] *Oak Ridge National Laboratory, USA*

The first results from CLARION2-TRINITY [1], a new charged-particle and HPGe array are presented: Coulomb excitation of ^{49}Ti. Ti-49 can be treated as a neutron hole plus semimagic ^{50}Ti core within the particle-core coupling scheme. Reduced electric quadrupole transition probabilities, or $B(E2)$ strengths, for the $2^+ \otimes f_{7/2}^{-1}$ multiplet members and candidate $p_{3/2} \otimes f_{7/2}^{-2}$ state were measured. The total electric quadrupole strength of ^{49}Ti is compared to the $B(E2; 0^+ \to 2^+)$ of the ^{50}Ti core in search of enhanced quadrupole collectivity, similar to that recently observed in ^{129}Sb relative to a ^{128}Sn core [2]. Both cases are near double-magic nuclei and have small core $B(E2)$ values. In the case of ^{49}Ti, however, a suppression of electric quadrupole strength is observed with respect to the ^{50}Ti core. This behavior is the opposite of previous empirical observations and expectations. The results are compared to shell-model calculations with state-of-the-art nucleon-nucleon interactions. The anomalous trend in the electric quadrupole collectivity is suggested to be primarily from destructive pn interactions within the nominal $f_{7/2}$ shell.



References

[1] T.J. Gray, J.M. Allmond *et al.*, Nucl. Instrum. Methods A **1041**, 167392 (2022).

[2] T.J. Gray, J.M. Allmond *et al.*, Phys. Rev. Lett. **124**, 032502 (2020).

M20 Experiment at JYFL

Tatiana Grečnárová[1] on behalf of M20 collaboration
[1] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*

The M20 experiment is a part of a broad research program to study the neutron-deficient odd-mass gold isotopes. Goal of the experiment was to identify new isomeric states in ^{179}Au and to investigate their decay pathways. Recent discovery of a new high-spin isomer at 1.7 MeV in ^{179}Au [1,2] provided a unique opportunity to populate and study non-yrast states of this nucleus. The experiment was performed at the University in Jyväskylä using the RITU separator with a non-standard constellation of detectors, which enabled use of high beam intensities from the cyclotron and thus greater data statistics to be aquired. Improved design of the focal plane chamber hosted 2 MWPC gas detectors and a fast scintilator for ion implantation. Three high-resolution BeGe detectors and 1 Clover HPGe detector surrounding the focal plane chamber were used for γ-ray detection. The ^{179}Au nuclei were produced in the ^{94}Mo(^{88}Sr,p2n)^{179}Au and ^{147}Sm(^{36}Ar,p3n)^{179}Au reactions. In the talk we will present motivation, outline the experimental setup and show a few preliminary results.

References

[1] M. Balogh *et al.*, Phys. Rev. C **106**, 064324 (2022).
[2] M. Balogh, Contribution to ISTROS 2023.

Signatures of shape coexistence in N=Z nuclei – studies of nuclear deformation in the vicinity of ^{40}Ca and ^{56}Ni

Katarzyna Hadyńska-Klęk[1]

[1] *Heavy Ion Laboratory, University of Warsaw, Poland*

The concept of magic numbers constitutes a cornerstone of nuclear physics research. Over the past few decades, it has been well established that closed-shell nuclei exhibit spherical shapes in their ground states. However, as nucleons are added to or removed from complete shells, they tend to deform the microscopic mass distribution. Studies of deformed shapes are of key importance for the advancement of nuclear structure physics, especially the origin of the observed enhanced deformation in the vicinity of doubly-magic mass nuclei. Furthermore, the observation of shape coexistence, in which several distinct nuclear shapes are observed to be present within a very small energy range in the nucleus, represents one of the most striking phenomena to be reported in atomic nuclei.

The observation of super-deformated structures (SD) at relatively low excitation energy in the mass A$\sim$40 around doubly-magic Z=N=20 ^{40}Ca nucleus [1], is one of the most important discoveries of the modern nuclear physics. Remarkably, the observed SD structures in these lighter nuclei are even less well understood than in heavier regions. Due to the vast reduction of nucleons involved and therefore complexity in comparison to heavy nuclei, A$\sim$40 constitutes an ideal ground for investigating exotic structures within various theoretical frameworks. Recently, the electromagnetic structure of the nucleus ^{42}Ca with the advanced AGATA γ-ray tracking array was studied [2]. It was demonstrated, for the first time, that it is possible to probe SD structures with Coulomb excitation. This work also provided the first direct experimental evidence for non-axially symmetric or triaxial SD shapes in the A$\sim$40 neighbourhood. The experimental studies of the deformation in this region are ongoing, aiming at investigating the origin of the emerging of SD structures coexisting with the normally deformed bands in the Ar-Ca-Ti isotopes.

Going more north-east from ^{40}Ca, the nickel isotopes offer a unique laboratory to investigate shape evolution in the vicinity of another doubly-magic nucleus ^{56}Ni (Z=N=28), which should exhibit similar structural properties to those observed in the Z=N=20 region. Indeed, observation of the SD structures was reported in ^{56}Ni, being explained as the result of $mp{-}mh$ excitations like in case of ^{40}Ca [3]. However, recently the questions on the validity of Z/N=28 as a good magic number have been brought up triggering the discussion on the deformation in the nickel region, including the signatures of shape coexistence. Microscopic and collective properties in the vicinity of ^{56}Ni shall be evaluated with the dedicated measurements of the deformation, also in the neighboring nuclei. To this end, the Coulomb excitation studies focused on the structure of ^{58,60,62}Ni isotopes are currently undertaken at several laboratories, including INFN LNL, IJC Lab Orsay and HIL Warsaw. These, together with the recent findings from the gamma-ray and electron spectroscopy measurements where the unexpectedly large E0 transition strengths for the $2^+_2 \rightarrow 2^+_1$ transitions of ^{58,60,62}Ni were reported [4], shall bring crucial information enabling the further discussion on the magical properties of Ni isotopes.

In this talk I will present the recent results from the Coulomb excitation measurements focused on Ca and Ni isotopes and the comparison with the state-of-the-art theoretical calculations.

References

[1] E. Ideguchi *et al.*, Phys. Rev. Lett. **87**, 222501 (2001)

[2] K. Hadyńska-Klęk *et al.*, Phys. Rev. Lett. **117**, 062501 (2016) and K. Hadyńska-Klęk *et al.*, Phys. Rev. C **97**, 024326 (2018)

[3] D. Rudolph *et al.*, Phys. Rev. Lett. **82**, 3763 (1999)

[4] L.J. Evitts *et al.*, Phys. Lett. B **779**, 396 (2018)

Stars, shapes and clusters

David Jenkins[1]
[1] *University of York, UK*

At first glance, the evolution of massive stars and shape coexistence as a facet of nuclear structure appear to have little in common. Nuclear structure certainly impacts on nucleosynthesis through the existence of shell closures. There is one long-standing example where shape coexistence is thought to play an important role, namely the existence of the Hoyle state which drives helium burning in massive stars. This 0^+ state appears at very low energy as the second excited state of ^{12}C. Such a state appears at very high energies in conventional approaches such as the shell model and can only be found at low energy through possessing a peculiar structure based on many particle-many hole excitations. There is much evidence that the Hoyle state represents a strongly deformed configuration based on building blocks of three alpha particles.

The question we set out to answer in this presentation is whether the Hoyle state paradigm is a unique and special case or whether it has wider application to nuclear reactions important to nuclear astrophysics. Here, we will look at the case of ^{12}C+^{12}C fusion. This reaction exhibits strongly resonant behaviour on and below the Coulomb barrier which makes it very difficult to extrapolate into the Gamow window relevant to massive stars. Nevertheless, the properties of this reaction are very important to the time scale and energy generation in massive stars.

Direct measurements of the ^{12}C+^{12}C reaction are very challenging. A significant breakthrough has been the development of particle-gamma coincidence detection to strongly reduce backgrounds and allow the first measurements in the Gamow window for the most massive stars [1]. Below these energies, indirect measurements are the only possible avenue of exploration. Studies of the ^{24}Mg(α,α') reaction have discovered several new 0+ states which sit just on the break-up threshold of ^{24}Mg into ^{12}C+^{12}C [2]. These states appear to be candidates for ^{12}C+^{12}C cluster states representing highly deformed configurations in ^{24}Mg; their existence may strongly accelerate carbon burning in massive stars [2]. The discovery of these states fits into a hierarchy of increasingly deformed configurations in ^{24}Mg providing strong evidence for shape coexistence and connecting shape coexistence with nuclear astrophysics.

References

[1] G. Fruet *et al.*, Phys. Rev. Lett. **124**, 192701 (2020).
[2] P. Adsley *et al.*, Phys. Rev. Lett. **129**, 102701 (2022).

Monopole decays and studies at iThemba LABS

Pete Jones[1] **and M.V. Chisapi**
[1] *Separated Sector Cyclotron Laboratory, iThemba LABS, Somerset West, South Africa*

Electric monopole (E0) transitions are closely tied to shape coexistence in atomic nuclei. The E0 transition strength, ρ^2(E0), is directly connected to nuclear mean-square charge radii. A large E0 transition strength is a reliable indicator of nuclear shape coexistence and strong mixing between admixture states of different deformation. Electric monopole transitions are possible between states of the same spin and parity such as two 0^+ states. They proceed via internal conversion and internal-pair formation.

Detecting conversion electrons and electron-positron pairs is normally done using magnetic lens spectrometers. A solenoid magnetic lens spectrometer was successfully refurbished and upgraded, giving it the capability to measure internal-pair formations (IPF) in addition to internal conversion electrons (ICE), at the iThemba Laboratory for Accelerator Based Sciences, in Cape Town, South Africa. The equipment can be coupled to other facilities or integrated into the existing beamlines. The smaller detector mount point in the original design of the electron spectrometer which only accommodated 300-500 mm^2 active area, 2-5 mm thick single crystal Si(Li) detectors was replaced by a mount point with provision for a much larger 2800 mm^2 active area, 11 mm thick segmented LEPS detector. The LEPS detector was adapted by replacing the thicker, 300 µm beryllium, window on the end-cap with a thinner, 0.5 μm Mylar window in order to minimise particle energy loss. Efficiency of the refurbished spectrometry system was optimised with the aid of Geant4 simulations and was estimated between 45% and 50% for ~1 MeV electrons or positrons at 500 G magnetic field.

The lens spectrometer was coupled with a mini-array comprised of seven Compton-suppressed HPGe Clover detectors, which gave additional experimental capabilities such as measuring γ-rays in coincidence with internal conversion electrons (ICE), and internal-pairs (IPF). An in-beam experiment involving a 30 MeV α-beam on a 96% enriched ^{50}Ti self-supporting target was performed to investigate the 3868.3 keV E0 ($0_2^+ \rightarrow 0_1^+$) electric monopole transition and its alternative E2 ($0_2^+ \rightarrow 2_1^+$) transition. The in-beam experimental campaign was not only a commissioning experiment for the newly refurbished magnetic lens spectrometer, but it was also part of the larger endeavour to characterise excited 0^+ states and E0 transitions in the N~Z~28 region of the nuclear chart.

In the future the spectrometer will be fully integrated into the K600 spectrometer at iThemba LABS operating in the 0-degree mode. Furthermore, when combined with other detectors, such as ALBA, utilising high detection efficiency for high-energy gamma rays, then a unique niche area of physics is feasible.

Results of these measurements will be presented together with future plans for the spectrometers and further studies.

Multiple shape coexistence in ^{100}Zr from a β-decay study with GRIFFIN

D. Kalaydjieva[1], H. Bidaman[2], P.E. Garrett[2], M. Rocchini[2,3], M. Zielińska[1], W. Korten[1], V. Bildstein[2], S. Pannu[2], Z. Ahmed[2], C. Andreoiu[4], D. Annen[4], G.C. Ball[5], G. Benzoni[6], S.S. Bhattacharjee[5], S. Buck[2], R.J. Coleman[2], S. Devinyak[5], I. Dillmann[5], R. Caballero-Folch[5], F.H. Garcia[7], A.B. Garnsworthy[5], B. Greaves[2], C.J. Griffin[5], G.F. Grinyer[8], E.Gyabeng Fuakye[8], G. Hackman[5], D. Hymers[2], R. Kanungo[9], K. Kapoor[8], E. Kasanda[2], N. Marchini[3], K.M. Mashtakov[2], A. Nannini[3], C. Natzke[5], B. Olaizola[10], K. Ortner[4], C.M. Petrache[11], M. Polettini[6], A.J. Radich[2], N. Saei[8], M. Satrazani[12], M. Siciliano[13], M. Singh[9], P. Spagnoletti[4], C.E. Svensson[2], D.A. Torres[5,14], R. Umashankar[5], V. Vedia[5], T. Zidar[2]

[1]*IRFU, CEA Saclay, Université Paris-Saclay, France*
[2]*University of Guelph, Canada*
[3]*INFN Firenze, Italy*
[4]*Simon Fraser University, Burnaby, Canada*
[5]*TRIUMF, Vancouver, Canada* [6]*INFN Milano, Italy*
[7]*Lawrence Berkeley National Laboratory, USA*
[8]*University of Regina, Canada*
[9]*Saint Mary's University, Halifax, Canada;* [10]*CERN, Switzerland*
[11]*IJCLab, Université Paris-Saclay, France*
[12]*University of Liverpool, UK*
[13]*Argonne National Laboratory, USA*
[14]*Universidad Nacional de Colombia, Bogotá, Colombia*

The dramatic shape transition of the ground states of nuclei with Z $\sim$ 40, appearing suddenly at N= 60 [1], has been the focus of numerous experimental studies as it provides a stringent test of existing theoretical models. Employing the powerful Monte-Carlo Shell Model (MCSM), Togashi et al. [2] suggested the coexistence of multiple low-energy structures with distinct shapes in ^{100}Zr. An inversion of configurations in ^{98}Zr and ^{100}Zr was proposed: the prolate configuration at $\sim$ 1 MeV in ^{98}Zr becomes the ground state in ^{100}Zr, while the spherical ground state of ^{98}Zr corresponds to a yet unobserved 0^+_4 level in ^{100}Zr that was predicted at excitation energy of about 1.5 MeV. Moreover, the calculations predict an oblate-deformed 0^+_2 state and a prolate-deformed 0^+_3 state in ^{100}Zr.

To further investigate the structure of ^{100}Zr and probe the validity of the theoretical predictions, a β-decay study [3], employing the powerful GRIFFIN spectrometer and its ancillary detectors, was carried out at the TRIUMF-ISAC facility.

Selected results will be presented, including the first observation of an enhanced transition between the $(2)^+$ state at 1196 keV – a candidate for the band head of a recently proposed [4] "proto-gamma" band – and the 0^+_3 state. This supports the interpretation of the $(2)^+$ state as a member of the deformed structure built on the excited 0^+_3 state, in agreement with the MCSM calculations. The experimental information on ^{100}Zr obtained from the present β-decay study, including lifetimes of low-lying states measured with the fast-timing technique, reveals structural similarities between ^{100}Zr and the neighbouring ^{98}Sr, for which the shape-coexistence scenario has been established from results of a Coulomb excitation study [5]. Finally, the 0^+_4 state has been identified with the spin-parity assigned using the γ-γ angular correlation technique. The observed structures are consistent with a multiple shape-coexistence scenario, in line with the MCSM predictions.

References

[1] P.E. Garrett *et al.*, Prog. Part. Nucl. Phys. **124** (2022) 103931.
[2] T. Togashi *et al.*, Phys. Rev. Lett. **117** (2016) 172502.
[3] D. Kalaydjieva *et al.*, Acta Phys. Pol. B Proc. Suppl. **16** (2023) 4-A15.
[4] W. Urban *et al.*, Phys. Rev. C **100** (2019) 014319.
[5] E. Clément *et al.*, Phys. Rev. Lett. **116** (2016) 022701.

E0 transitions and shape coexistence in light nuclei

Tibor Kibédi[1]

[1] *Department of Nuclear Physics and Accelerator Applications, Australian National University, Canberra, ACT Australia*

Nuclear shape coexistence is a phenomenon in which the atomic nucleus can take different shapes at low excitation energies. The presence and behaviour of 0^+ states in even-even nuclei and their association with nuclear shapes play a pivotal role in understanding shape coexistence [1]. E0 transitions are the only possible decay path between two $J^\pi = 0^+$ states. The nuclear E0 transition strength, $\rho^2(E0)$, provides a unique probe into these nuclear shapes. On the fundamental level, double magic nuclei, like ^{16}O and ^{40}Ca, are treated in the shell model as having spherical inert cores. Our recent study of E0 transitions in ^{40}Ca [2], between the spherical ground, the normal-deformed and super-deformed states, indicates that the ground state is neither spherical nor inert. It is expected that the pattern of shape coexistence in and near ^{56}Ni (N=Z=28) will be similar to ^{40}Ca (N=Z=20). However, our recent studies of nuclei adjacent to ^{56}Ni have found evidence of E0 transitions in Z=28 isotopes and N=28 isotones, but not in neighbouring nuclei.
In this talk selected results [3-5] will be used to explore the evolution of shape coexistence in and around the N=28 Cr, Mn and Fe nuclei. The experiments, using conversion electron and electron-positron pair spectroscopy, were performed at the Heavy Ion Accelerator Facility at the Australian National University using the Super-e superconductive spectrometer.

References

[1] T. Kibédi, A.B. Garnsworthy and J.L. Wood, Prog. Part. and Nucl. Phys. **123** (2022) 103930.
[2] E. Ideguchi, *et al.*, Phys. Rev. Lett. **128** (2022) 252501.
[3] T.K. Eriksen, PhD thesis, ANU 2018.
[4] J.T.H. Dowie, *et al.*, EPJ Web of Conferences **232** (2020) 04004.
[5] L.J. Evitts, *et al.*, Phys. Lett. B **779** (2018) 396.

Acknowledgement

Project supported by the Australian Research Council - DP140102986 and DP17010167.

Links between the compound nucleus' shape and the deformation of the residual nuclei studied by GDR γ-decay

Maria Kmiecik[1]

[1] *The Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*

The GDR has been proven to constitute a very good tool for nuclear shape studies [1] as the line-shape of the GDR reflects the shape of a nucleus in which GDR was excited. The studies of giant resonance decay provided information on the relation between the properties of evaporation residues produced in compound nucleus decay and the characteristics of hot compound nucleus. Particularly, it was shown that the shape of hot nucleus may determine the deformation of the decay product. Such dependence was observed for the ^{46}Ti compound nucleus decay leading to ^{42}Ca residue in which preferential feeding of highly deformed band in ^{42}Ca by the low energy part of GDR was evidenced [2]. Similar finding was reported for ^{147}Eu compound nucleus decaying to deformed states of ^{143}Eu [3]. Also by the measurement of the GDR decay built in ^{216}Rn at high-spins the information on the deformation at the fission limit was obtained [4].

Our group recently conducted similar studies at IJCLab Orsay. The experiment aimed at the investigation of the link between the characteristic of the compound nucleus and residual nuclei, by the measurement of γ-decay of GDR excited in ^{192}Pt compound nucleus leading to ^{188}Pt residue [5]. This nucleus is known for its ground state prolate shape and tri-axial band based on 12^+ state. The experimental method based on simultaneous measurement of high-energy gamma rays from the GDR decay and low-energy transitions enabled to get the information on feeding of particular residual states. The ^{192}Pt compound nuclei were created with fusion reaction using beam of ^{18}O at 90 MeV on ^{174}Yb target. The experimental setup consisted of the PARIS [6] and nuBall arrays. 32 PARIS ($LaBr_3$/$CeBr_3$ + NaI) phoswiches were employed to measure high-energy γ rays from the GDR decay, while low-energy discrete transitions were measured by 24 clover HPGe and 10 coaxial Ge detectors of nuBall.

During the talk the method of studies will be presented together with the obtained results. The preliminary results of the recent measurement will be discussed as well. Also the idea of follow-up experiment performed in November 2022, using more efficient setup consisting of 72 PARIS detectors and nuBall2 array to investigate the ^{80}Sr compound nucleus decay to the states of various deformation of ^{76}Kr residue, will be shown.

References

[1] P. Bortignon, A. Bracco, and R. A. Broglia, Giant Resonances: Nuclear Structure at Finite Temperature (Gordon Breach, New York, 1998).
[2] M. Kmiecik *et al.*, Acta Phys. Pol. B **36** (2005) 1169.
[3] G. Benzoni *et al.*, Phys. Lett. B **540** (2002) 199.
[4] M. Kmiecik *et al.*, Phys. Rev. C **70** (2004) 064317.
[5] M. Ciemała *et al.*, Acta Phys. Pol. B, in print.
[6] A. Maj *et al.*, Acta Phys. Pol. B **40** (2009) 565.

Acknowledgement

This work was supported by the National Science Centre, Poland (NCN) under contracts No. 2017/01/X/ST2/00439 and 2018/31/D/ST2/03009.

Decay Spectroscopy of Deformed, Neutron-rich Nuclei at ANL

Filip G. Kondev[1]

[1]*Physics Division, Argonne National Laboratory, Lemont, IL 60439, U.S.A*

Properties of deformed, neutron-rich nuclei in the A∼110 and 160 mass regions are important for achieving better understanding of the nuclear structure where little is known owing to difficulties in the production of these nuclei at the present RIB facilities. They are essential ingredient in the interpretation of the r-process nucleosynthesis and are needed in fission-like applications since theoretical models depend sensitively on the nuclear structure input. Predicated on these ideas, a dedicated decay spectroscopy experimental program has been initiated at Argonne National Laboratory, by combining the CARIBU radioactive beam facility with the newly developed Gammasphere decay station. The initial focus was on several deformed odd-odd nuclei, where β^- decays of both the ground state and an excited isomer were investigated. Because of the spin difference, a variety of structures in the daughter nuclei were selectively populated and characterized, which in turn provided information about the structure of the isomers. Mass measurements using the Canadian Penning Trap aimed at discovering of long-lived isomers in these regions and at determining of their excitation energies were also carried out.
Overview of the decay spectroscopy program at ANL will be presented together with results from recent experiments and comparison with multi-quasiparticle blocking calculations. The effect of K-forbiddenness on the β^--decay strength will also be discussed.

Acknowledgement

Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and the National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation R & D (NA-22).

New insight into the nuclear structure at shell closures from laser spectroscopy

Ágota Koszorús[1,2], CRIS Collaboration CERN

[1]*KU Leuven,Leuven, Belgium*
[2]*SCK CEN, Mol, Belgium*

The nuclear electromagnetic moments and changes in the mean-squared charge radii are sensitive tools to investigate phenomena emerging in short-lived isotopes [1]. These properties, extracted from laser spectroscopy experiments, are often essential to critically examine our understanding of the nuclear structure, and its evolution towards edges of the nuclear landscape [2,3]. In this contribution, recent results will be presented from collinear laser spectroscopy experiments, exploring the changes in the nuclear structure in the tin region (Z=50) towards the N=50 and N=82 shell closures. The role of collectivity will be examined by looking at the charge radii and the electromagnetic moments of Ag, In and Sn isotopes.
In addition, recent highlights will be shown presenting the first measurement of a charge radius beyond the N=20 shell closure in the island of inversion, and progress to fill the gap in our knowledge about the proton-rich landscape in light isotopes.

References

[1] X.F. Yang *et al.*, Journal Progress in Particle and Nuclear Physics **129** (2023) 104005.
[2] Á. Koszorús *et al.*, Nature Physics **17** (2021) 439-443.
[3] A.R. Vernon *et al.*, Nature **607** (2022) 260-265.

Study of ^{36}Ca: Colossal Mirror Energy Differences, magicity at N = 16 and the ^{35}K$(p,\gamma)^{36}$Ca reaction for astrophysics

Louis Lalanne[1]
[1] *CERN, Switzerland*

The ^{36}Ca nucleus has several fascinating properties bringing together multiple fields of nuclear physics. In the mirror pair ^{36}Ca-^{36}S, the Coulomb interaction induces large isospin symmetry breaking effects that act as a magnifying glass of the structure of the excited states. The study of the corresponding mirror energy differences then allows to probe their structures and shapes. Furthermore, with 16 neutrons and 20 protons, ^{36}Ca is expected to show features of a doubly magic nuclei. The magicity of the N=16 sub-shell closure has already been highlighted far from stability, in the neutron rich ^{24}O but have still not been evidenced in the proton rich region. Finally, the ^{35}K(p,γ)^{36}Ca reaction has been identified as one of the ten (p,γ) reactions having the largest impact on the luminosity profile emitted during Type I_a X-ray burst. In this presentation, experimental results obtained at GANIL using (p,d) and (p,t) transfer reactions on ^{35}Ca and ^{36}Ca will be presented, together with their implication in the study of isospin symmetry breaking, shell evolution and nuclear astrophysics.

Nuclear Collective Vibrational Modes studied at the Proton Therapy Center CCB in Krakow

Adam Maj[1]

[1] *IFJ PAN Krakow, Poland*

The atomic nuclei, although they are quantal objects, may exhibit many features, which are known from the macroscopic world. To one of them belong different types of collective vibration, known as Giant Resonances, or recently studied, and important for the understanding of the creation of elements in the Universe, so called Pygmy Resonances. The studies of the γ decay of the Giant and Pygmy Resonances continue to be the hot topics, and are conducted by many groups in the world.

Recently this topic became one of the main research subjects at the proton therapy center CCB (Cyclotron Center Bronowice) at IFJ PAN Krakow. The collective vibrations in stable nuclei were excited via the inelastic scattering of the fast (70-230 MeV) protons from the Proteus cyclotron in CCB. The scattered protons were detected in the detector KRATTA (Krakow Array of Triple Telescope Array), providing information of the excitation energy. The high-energy γ-rays were measured in the 2 PARIS (Photon Array for studies with Radioactive Ion and Stable beams) clusters and 4 large volume $LaBr_3$ scintillators.

In the talk I will present the status of the CCB facility in Krakow, the recently achieved results from the nuclear physics experiment, focusing on studies of Collective Vibrational Modes. Moreover, I will present the research plans for the near future. In addition, if time permits, I will inform about the status and plans of constructing the PARIS array, used in European facilities including CCB.

Beta-decay study of the shape coexistence in ^{98}Zr

Konstantin Mastakov[1], P. Garrett[1], B. Olaizola[1,2], A. Diaz-Varela[1], A. Radich[1], A. Chester[3], A. Garnsworthy[4], A. Laffoley[1], B. Hadina[1], B. Singh[5], C. Svensson[1], C. Andreoiu[3], D. Cross[1], E. Rand[1], G. Demand[1], G. Deng[1], G. Ball[4], G. Hackman[4], H. Dawkins[1], J. Park[4], M. Moukaddam[4], M. Rajabali[4], P. Voss[3], U. Rizwan[3], V. Bildstein[1], Z. Wang[4]

[1] *Department of Physics, University of Guelph, Guelph, Canada*
[2] *ISOLDE-EP, CERN, Geneva, Switzerland*
[3] *Department of Chemistry, Simon Fraser University, Burnaby, Canada*
[4] *TRIUMF, Vancouver, Canada*
[5] *Department of Physics & Astronomy, McMaster University, Hamilton, Canada*

Understanding the phenomenon of shape evolution in atomic nuclei has been one of the main quests in nuclear physics. While throughout the nuclear chart the evolution of a spherical ground-state shape into a deformed one is usually a gradual process, in the Zr isotopic chain an abrupt shape transition is observed at N=60. This dramatic onset of deformation in ^{100}Zr was recently well reproduced in the state-of-the-art Monte Carlo Shell Model calculations [1, 2], which also predict that the same deformed configuration may coexist at higher excitation energies in the lighter Zr isotopes. The ^{98}Zr is of particular interest in this regard as it is a transitional nucleus which lies on the interface between both spherical and deformed nuclear phases. Thus, significant amounts of experimental and theoretical research efforts have been made to study the shape coexistence phenomena in ^{98}Zr [3,4,5,6]. While they demonstrate a good overall description of the ^{98}Zr nuclear structure, the interpretation of the higher-lying shape coexisting bands is still uncertain. In particular, several discrepancies between theoretically calculated and experimentally deduced reduced transition probabilities were noted, highlighting the need for further investigations.
Based on the above, a β-decay experiment was performed at TRIUMF-ISAC facility utilising the 8π spectrometer in conjunction with auxiliary β-particle detectors to measure the branching ratios and multipolarity mixing ratios for the transitions in ^{98}Zr. The high-quality and high-statistics data obtained with this setup allowed for the determination of branching ratios for very weak transitions important for assigning band structures. Furthermore, gamma-gamma angular correlation measurements enabled both spin assignments and mixing ratio determinations. The new results will be presented, and discussed in relation to both the MCSM and recent IBM configuration mixing calculations.

References

[1] T. Otsuka and Y. Tsunoda, J. Phys. G: Nucl. Part. Phys. **43**, 024009 (2016).
[2] T. Togashi, Y. Tsunoda, T. Otsuka, and N. Shimizu, Phys. Rev. Lett. **117**, 172502 (2016).
[3] P. Singh, W. Korten *et al.*, Phys. Rev. Lett. **121**, 192501 (2018).
[4] V. Karayonchev, J. Jolie *et al.*, Phys. Rev. C **102**, 064314 (2020).
[5] J. E. Garcia-Ramos, K. Heyde, Phys. Rev. C **100**, 044315 (2019).
[6] P. Kumar, V. Thakur *et al.*, Eur. Phys. J. A **57**, 36 (2021).

Deconvolution methods and their use to improve resolution in γ-ray spectra

Vladislav Matoušek[1]

[1] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*

The accuracy and reliability of the analysis of nuclear spectra is limited mainly by the resolution of detectors, electronics used, and the presence of noise in the measured spectra. The peaks as the main carrier of spectrometric information are very frequently positioned close to each other. This makes it difficult to accurately measure the energy and intensity of the spectral lines because of the contributions from the adjacent objects and background. However, this effect can be corrected to some extent by characterizing the response function of the measurement chain and the consequent deconvolution of data. The response function depends on the energy of the specific peak in the spectrum and time. It can be estimated e.g. from the known singlets in the corresponding energy regions. Once the response function is estimated, the energy or time resolution of the spectra can be improved using the deconvolution process, leading to e.g. separation of dublets or multiplets, etc. The deconvolution methods are very efficient and widely used tools to improve the resolution in spectrometric data. They are of great importance mainly in the tasks connected with the decomposition of low amplitude overlapped peaks in the presence of noise. But the deconvolution operation is an ill-posed inverse problem due to the noise and granularity of the data. To solve this problem, regularization is necessary to guarantee the robustness of the solution.

In the talk, several deconvolution methods and their decomposition capabilities from the resolution point of view will be presented. We have proposed improvements in the efficiency of the iterative deconvolution methods by introducing modifications into the deconvolution process, e.g. noise suppression operations during iterations, and we improved blind deconvolution methods. We will illustrate their suitability for processing noisy spectrometric data. It will be shown, that using the presented developed algorithms we are able to improve the resolution in spectrometric data. The methods are able better detect hidden peaks in the noisy gamma-ray spectra and decompose the overlapped peaks by concentrating the peak areas into a few channels.

The Heavy Ion Laboratory at the University of Warsaw - an European facility in the centre of Poland

Paweł J. Napiorkowski[1]

[1] *Heavy Ion Laboratory, University of Warsaw, Poland*

„Nuclear Physics News" in 1994 reported: „*New facility is born. It has been a good season for Polish heavy ion physicists and for Warsaw champagne dealers, as well. At the end of November 1993, the stocks of champagne were depleted after the first successful acceleration of 32 MeV $^{20}Ne^{2+}$ beam in the Warsaw Heavy Ion Cyclotron[...]*".
Since then, the world and the Heavy Ion Laboratory at the University of Warsaw have changed. Today, the Warsaw U-200P cyclotron delivers beams of heavy ions for experiments conducted by international experimental teams with the ICARE, EAGLE, and NEDA setups. Research opportunities offered by the HIL infrastructure are not limited to nuclear spectroscopy only, but also extend to radiobiology, materials studies and medical applications. A selection of results obtained in this European transnational access facility located in the centre of Poland and plans for the very near future will be presented.

Wobbling and oblate rotation

Costel M. Petrache[1]
[1] *Université Paris-Saclay, IJCLab, CNRS-IN2P3, Orsay, France*

The wobbling motion was intensively studied in the last few years, mainly due to the introduction of the transverse wobbling concept, which enriched the diversity of collective modes exhibited by triaxial nuclei. Many experimental and theoretical groups intensively studied the low-spin wobbling in odd-even nuclei and medium-spin wobbling in even-even nuclei. While the experimental evidence and theoretical interpretation in terms of transverse or longitudinal wobbling of the low-spin non-yrast bands is seriously questioned in recent works, the transverse wobbling in two-quasiparticle bands observed at medium spin in even-even nuclei seems to be confirmed both experimentally and theoretically. Bands built on two-quasiparticle configurations interpreted as transverse wobbling have been recently identified first in ^{130}Ba, and shortly later in ^{136}Nd. Recent theoretical works revealed the inadequacy of the wobbling interpretation of these low-spin bands, which are naturally described by tilted precession (TiP).
Another topic of current interest is the existence of collective oblate shapes and their type of motion. Solid evidence of bands built on oblate shapes close to the ground state in ^{119}Cs, and at very high spin and temperature in ^{137}Nd has been recently published. The collective oblate band observed in ^{137}Nd up to 5 MeV above the yrast line offers the unique opportunity to investigate the decrease of decoherence with the increasingly dense background of quasiparticle excitations, while the strongly populated oblate band in ^{119}Cs offers the first example of prolate-oblate shape coexistence in the $A \approx 120$ mass region. These new experimental results and their interpretation will be discussed.

Shape coexistence in neutron-deficient ^{190}Pb

Adrian M. Plaza[1,2], J. Pakarinen[1], P. Papadakis[3], R.-D. Herzberg[2], P. T. Greenlees[1], SAGE Team[1,2]

[1]*Accelerator Laboratory, Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland.*
[2]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, United Kingdom.*
[3]*Nuclear Physics Group, STFC Daresbury Laboratory, Keckwick Lane, Warrington, Cheshire, WA4 4AD, United Kingdom*

Shape coexistence is an broad phenomenon with manifestations all over the nuclear chart [1]. In the neutron-deficient lead region when approaching the neutron mid-shell N = 104, collective intruder configurations give rise to oblate and prolate shapes competing with the spherical ground-state, in particular in 190Pb. Wealth of information on the nuclear structure is connected to these different potential well minima. Diagonal E2 matrix elements will be determined from the Coulomb excitation IS494 experiment [2] performed at ISOLDE. In this study, we have performed two other experiments to address this phenomenon via the best complementary fingerprints of it.
Simultaneous measurement of internal conversion electrons and γ rays was allowed thanks to the SAGE spectrometer [3] within the first campaign where is was used coupled to MARA (Mass Analysing Recoil Apparatus) [4,5], a vacuum mode recoil separator. The desired nucleus was produced via the fusion-evaporation reaction ^{159}Tb(^{35}Cl,4n), at beam energy of 165 MeV, in the Accelerator Laboratory at the University of Jyväskylä (JYFL) [6]. The accurate measurement of strong E0 inter-band transitions provides valuable information between states with different mean-square charge radii. These monopole transition strengths and shape mixing amplitudes can be calculated through the B(E2) values or lifetimes of the side-band transitions, if available. Besides, spectroscopic information has been gathered for the structures above the 11^- and 12^+ isomeric states.
Whereas previous experimental studies have assigned the yrast band with a spherical shape [7], theoretical calculations beyond mean-field and within the interacting boson model (IBM) have shed light on a possible oblate configuration dominance [8,9]. In order to clarify this and to investigate the shape mixing at low-spin and above the isomeric states, an experiment has been conducted in March 2023 at JYFL to provide more insight into the shape mixing in this region, via the Recoil Distance Doppler-Shift (RDDS) method.

References

[1] K. Heyde and J. L. Wood, Rev. Mod. Phys. **83** (2011) 1467.
[2] T. Grahn, J. Pakarinen *et al.*, IS494 (2009) 1-10.
[3] J. Pakarinen *et al.*, Eur. Phys. J. A **50** (2014) 1-11.
[4] J. Sarén *et al.*, Nucl. Instrum. Methods Phys. Res. B **266** (2008) 4196-42.
[5] J. Uusitalo, J. Sarén, J. Partanen and J. Hilton, Acta Phys. Pol. B **50** (2019) 319-327.
[6] A. M. Plaza *et al.*, in preparation.
[7] G. D. Dracoulis, A. P. Byrne and A. M. Baxter, Phys. Lett. B **432** (1998) 37-44.
[8] V. Hellemans, S. De Baerdemacker and K. Heyde, Phys. Rev. C **77** (2008) 064324.
[9] J. M. Yao, M. Bender and P.-H. Heenen, Phys. Rev. C **87** (2013) 034322.

Curious collective modes in nuclei - predictions by QRPA and possible footprints

Anton Repko[1], **V.O. Nesterenko**[2], **J. Kvasil**[3]
[1] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia.*
[2] *Laboratory of Theoretical Physics, Joint Institute of Nuclear Research, Dubna, Russia.*
[3] *Institute of Particle and Nuclear Physics, Charles University in Prague, Czech Republic.*

A large number of excited states in the nuclei can be understood in terms of collective motion, such as rotation or vibration. Nevertheless, there is almost always an admixture of single-particle degrees of freedom, which will modify the detailed structure of particular excitations and their energy. I will discuss examples of vortical states [1], hypothesized spin-scissor states [2,3] and anomalous deformation dependence of moments of inertia.
In order to properly describe such excitations, a microscopic method is needed, which can cover also heavy and deformed nuclei. These criteria are fulfilled by Quasiparticle Random-Phase Approximation (QRPA), which is a direct extension of microscopic mean-field models (such as energy-density functionals (EDF) or Hartree-Fock methods) for the treatment of excited states. As a trade-off, the calculations are usually restricted to even-even nuclei and one-phonon excitations (i.e., superpositions of two-quasiparticle configurations). In our case, we employ the Skyrme functional with pairing [4].
The QRPA method is mainly suitable for the calculation of giant resonances, where it also allows to visualize the familiar transition-current fields (such as proton-vs-neutron vibration in GDR ($E1$) case, β- and γ-vibrations in GQR ($E2$) case, scissor vibrations in $M1$ case etc.). Such transition-current plots [5] can be then employed to reveal another interesting excitations, for example, in low-energy regions.
However, accurate numerical description of the low-energy states requires a suitable treatment of spurious states, which usually contaminate the low-lying excitations. We developed methods for removal of spurious admixtures, which can be applied after [6] or before [7] the QRPA matrix diagonalization.
The predicted collective modes can serve as a testing ground for the accuracy of nuclear interactions, and their application for the nuclear matter, astrophysics etc. For this aim, an experimental verification is needed for the predicted transition currents in the nuclear excited states. I will briefly discuss inelastic electron scattering as a perspective method in this regard [8,9].

References

[1] V.O. Nesterenko, A. Repko, J. Kvasil and P.-G. Reinhard, Phys. Rev. Lett. **120** (2018) 182501.
[2] E.B. Balbutsev, I.V. Molodtsova and P. Schuck, Phys. Rev. C **97** (2018) 044316.
[3] V.O. Nesterenko, P.I. Vishnevskiy, J. Kvasil, A. Repko and W. Kleinig, Phys. Rev. C **103** (2021) 064313.
[4] A. Repko, Theoretical description of nuclear collective excitations. Ph.D. Thesis, Charles University in Prague (2015). arXiv:1603.04383 [nucl-th]
[5] A. Repko, P.-G. Reinhard, V.O. Nesterenko and J. Kvasil, Phys. Rev. C **87** (2013) 024305.
[6] A. Repko, J. Kvasil and V.O. Nesterenko, Phys. Rev. C **99** (2019) 044307.
[7] J. Kvasil, A. Repko and V.O. Nesterenko, Eur. Phys. J. A **55** (2019) 213.
[8] A. Repko and J. Kvasil, Acta Phys. Pol. B Proc. Suppl. **12** (2019) 689.
[9] V.O. Nesterenko, A. Repko, J. Kvasil and P.-G. Reinhard, Phys. Rev. C **100** (2019) 064302.

Probing the most exotic silver isotopes

Mikael Reponen[1], **R. P. de Groote**[2], **Z. Ge**[3], **I. D. Moore**[1]
[1] *Accelerator Laboratory, Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland.*
[2] *Instituut voor Kern- en Stralingsfysica, KU Leuven, B-3001 Leuven, Belgium*
[3] *GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*

The heaviest bound self-conjugate doubly-magic nucleus, ^{100}Sn, is the cornerstone of the nuclear chart region. Its proximity to the proton drip-line, role as the end-point in an alpha-decay chain, having the largest Gamow-Teller strength so far measured in allowed nuclear β-decay, and features such as the tensor force critically affecting its shell-structure make it, and its immediate vicinity, exciting for nuclear physics studies [1]. However, as the reaction cross-sections drop rapidly towards the N=Z line, many of the nuclear properties in the immediate region of ^{100}Sn have not been studied.
The advances in Penning trap techniques, combined with efficient inductively heated hot cavity catcher laser ion source (HCLIS), have recently enabled ultra-sensitive Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) assisted in-source resonance ionization spectroscopy [2]. This novel combination of techniques, realised at the IGISOL facility [3] at the University of Jyväskylä Accelerator Laboratory, was used to cross the N=50 shell closure near ^{100}Sn for the first time with the charge-radii measurement of ^{96}Ag. Since then, further measurements using similar techniques have extended down to ^{95}Ag.
In this contribution I will present the breakthrough experimental setup and its first application to the measurement of the charge radii of ^{96}Ag. I will also present the most recent results on masses, charge radii and magnetic moment down to ^{95}Ag. Furthermore, the ongoing campaign to resolve the long-standing conundrum of the two-proton decay in ^{94}Ag will be discussed along with prospects of delving even further even further into the immediate region near ^{100}Sn.

References

[1] M. Górska *et al.*, Physics **4(1)** (2022) 364-382.
[2] M. Reponen *et al.*, Nature Communications **12(1)** (2021) 4596.
[3] I. D. Moore *et al.*, Hyperfine Interactions **223(1)** (2014) 17-62.

CTADIR - Cryogenic Target for DIrect Reactions

Matúš Sedlák[1], A. Gottardo[1], I. Zanon[1], A. Goasduff[1], R. Pengo[1], M. Balogh[1], M. Rigato[1], F. Crespi[2,3], I. Lombardo[4]

[1] *INFN Laboratori Nazionali di Legnaro, Viale dell'Università 2, 35020 Legnaro, Italy*
[2] *INFN, Sezione di Milano, Milano, Italy*
[3] *Università degli Studi di Milano, Milano, Italy.*
[4] *INFN, Sezione di Catania, Catania, Italy.*

Direct nuclear reactions of exotic beams with cryogenic targets are powerful tools for studying the single-particle structure of atomic nuclei. Reactions like (^{4}He,^{3}He) or (^{3}He,d), where one nucleon is exchanged between projectile and target nucleus, are fundamental to explore the evolution of single-particle nuclear structure in neutron-rich nuclei. The study of nuclei far from stability increasingly relies on measurements performed at exotic Radioactive Ion Beam (RIB) facilities, like upcoming SPES at LNL. These reaction Q-values are well matched with typical beam energies of the ALPI accelerator (10 - 15 MeV/u), which leads to cross sections of several mbarns for neutron-rich ion beams. However, parameters of aforementioned RIBs, which typical energies around 10 MeV/u and their usually low intensities around 10^4 pps imply the necessity of a scattering centre density larger than 10^20 at/cm^2. In this context, the CTADIR [1,2,3] target has been developed, aiming at coupling a Helium cryogenic target to modern compact-geometry state-of-the-art detector arrays such as the AGATA [4] gamma-ray tracking detector array and GRIT [5] silicon detector for light charged particles. With the CTADIR cryogenic target, where helium is kept at temperatures around 10 K, the desired target density can be obtained within only 4 mm along the beam direction. The talk will describe the CTADIR construction, the status of the project, vacuum, pressure and cryogenic performance and the target commissioning, which is foreseen for Summer 2023.

References

[1] M. Sedlák *et al.*, Nuovo Cimento **C 45** (2022) 108.
[2] A. Goasduff *et al.*, LNL Annu. Rep. **262** (2021) 41.
[3] M. Sedlák *et al.*, LNL Annu. Rep. **266** (2022) 36.
[4] S. Akkoyun et *al., N*ucl. Instr. Meth. **A 668** (2012) 26.
[5] J.-J. Dormard *et al.*, Nucl. Instr. Meth. **A 1013** (2021) 165641.

Acknowledgement

We acknowledge the PRIN 2017 call (project 2017P8KMFT) for CTADIR project funding.

Investigation of shape coexistence via lifetime measurements

Franziskus von Spee[1], **C. Fransen**[1], **M. Beckers**[1], **F. Dunkel**[1], **A. Esmaylzadeh**[1], **J. Jolie**[1], **C. Lakenbrink**[1], **C. Müller-Gatermann**[2], **N. Warr**[1]

[1] *University of Cologne, Cologne, Germany*
[2] *Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*

Shape coexistence is a widely spread phenomenon, where different shapes emerge at similar excitation energies in the same nucleus. In a recent paper, P. Garrett *et al.* give an overview over different experimental signatures of shape coexistence [1]. The measurement of absolute transition strengths allows to detect signatures for shape coexistence in a nucleus. These observables can be determined from lifetimes of the related states. Our group has thus conducted several lifetime measurements using the Recoil Distance Doppler-Shift (RDDS) method to investigate shape coexistence in different regions of the nuclide chart. Using different examples from recent experiments, we will present several cases were lifetime measurements have helped to identify some of these experimental signatures.
In the first case, lifetimes in the neutron rich ^{102}Mo were measured using a transfer reaction [2]. Transfer reactions populate low-lying, low-spin states but also result in a relatively large recoil velocity for the reaction product and hence give the opportunity to study low-lying off-yrast states with the RDDS method that are not accessible with other reaction mechanisms. The measured lifetime of the 0_2^+ allowed to calculate the E0 transition strength and extend the picture of shape coexistence in the Mo isotopes.
Shape coexistence in Te isotopes has been suspected for a long time, but experimental evidence is still scarce. In a recent experiment, lifetimes were measured in neutron deficient ^{116}Te again using a transfer reaction. Also here, the lifetime of the 0_2^+ was measured. Additionally a candidate for a band structure on top of the 0_2^+ state was found. To clarify the spin and parity assignment in ^{116}Te, a second experiment was performed populating the nucleus via β-decay.
Further, in neutron deficient nuclei in the A=180 region very prominent examples for shape were found, for example in Hg and Pt isotopes around neutron mid-shell. Here, we will present our new data in this region and relate those to the structural interpretation, especially with respect to a development in very neutron deficient Hg, Pt, W and Os isotopes where existing experimental data cannot be explained with nuclear models so far.

References

[1] P. Garrett *et al.*, Prog. Part. Nucl. Phys. **124** (2022) 103931.
[2] A. Esmaylzadeh *et al.*, Phys. Rev. C **104** (2021) 064314.

Alpha-decay fine structure in ^{179}Hg and ^{177}Au

Andrej Špaček[1], **Andrej Herzáň**[1], **Matúš Sedlák**[2,1], **Martin Venhart**[1]

[1] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*
[2] *INFN Laboratori Nazionali di Legnaro, Viale dell'Università 2, 35020 Legnaro, Italy*

Alpha decay has been known for a long time to be a powerful probe to study exotic nuclei far from the β-stability line. Moreover, the α-decay fine structure, discovered by Rosenblum in 1929 [1], allows the study of properties of low-lying excited states in these nuclei, that are difficult to populate due to low reaction cross-sections.
The results of two experiments performed at JYFL Finland will be discussed. Particularly, the α-decay fine structure of ^{179}Hg and ^{177}Au has been investigated. A new α-decay branch in ^{179}Hg has been identified. Additionally, a conversion coefficient of the transition depopulating the aforementioned α-decay branch was measured for the first time, confirming the assumptions made in [2]. One new α-decay branch in ^{177}Au populating the 156 keV excited state in ^{173}Ir was observed, confirming the tentative assignment made in [3]. Two additional transitions in ^{173}Ir were observed and will be discussed.

References

[1] S. Rosenblum, C. R. Acad. Sci. Paris **188**, 1401 (1929).
[2] P. Peura *et al.*, Phys. Rev. C **89**, 024316 (2014).
[3] R. D. Harding *et al.*, Phys. Rev. C **104**, 024326 (2021).

Weakly Collective Nuclei - a Moments Perspective

Andrew E. Stuchbery[1]

[1] *Department of Nuclear Physics and Accelerator Applications, The Australian National University, Canberra, ACT 2601, Australia*

Weakly collective nuclei are defined here as those that occur between nuclides that have a few valence nucleons outside a doubly magic core and those with many valence nucleons that show clear rotational bands. In other words, they fall between the realm of the nuclear shell model and the rotor model. With advances in computing capability, the shell model as a large-basis configuration-interaction problem begins to reach such nuclei. But how successful can the shell model be? How does nuclear collectivity emerge? Does it require interactions well beyond the normal shell-model valence space? How well do we really understand weakly collective nuclei [1]? Experimental results obtained by the Australian National University Nuclear Structure group and their collaborators will be highlighted, with a focus on insights gained by confronting model calculations with experimental data on electromagnetic decays and moments. There is increasing evidence that collectivity in nuclei emerges immediately as deformation and rotation, not vibration, and that the weakly deformed shapes tend to be triaxial. The existence of low-excitation vibrational states (multiphonon states), which has been one of the foundational concepts of nuclear structure, is strongly questioned. Moreover, the magnetic moments of weakly collective nuclei suggest that there is a class of nuclei, exemplified by the Te [2] and Xe [3] isotopes near ^{132}Sn, that could be described as *pre-collective*, in that they begin to show collectivity in the low-excitation structure, but single-particle (seniority) structures also persist. Collectivity is emerging, but states that are 'more collective' exist along with states that are 'less collective'.

The above discussion applies to heavier nuclei, where the nearest doubly magic nuclides have $N > Z$. A second direction concerns shape coexistence in the classic doubly magic shell-model cores with $N = Z$, namely ^{16}O and ^{40}Ca. The existence of relatively low-excitation deformed multiparticle-multihole states in these nuclei has long been known. However, measured electric monopole transition strengths are now determining the degree of shape mixing, with increasing evidence that these presumed inert, spherical shell-model cores are in fact deformed in their ground states [4,5]. One puzzle is that while the shell model (understandably) fails to describe the magnetic moments of the first-excited 2^+ states of nuclei with two nucleons added to these doubly magic nuclei [1], it better describes the moments as the number of nucleons in the valence space increases. There are open questions concerning the emergence of collectivity and shape co-existence in the f and fp shells that we are investigating through measurements of magnetic moments and electric monopole transition strengths [5].

References

[1] A.E. Stuchbery and J.L. Wood, Physics **4** (2022) 697.
[2] Ben Coombes, PhD Thesis, ANU (2021) unpublished.
[3] G. Jakob *et al.*, Phys. Rev. C **65** (2002) 024316.
[4] E. Ideguchi *et al.*, Phys. Rev. Lett. **128** (2022) 252501.
[5] Tibor Kibédi, Contribution to ISTROS 2023.

Acknowledgement

Supported by Australian Research Council Discovery grants no DP210101201, DP170101673 and DP140102986.

Study of multiparticle photonuclear reactions at energy $E_{\gamma\max}$ up to 100 MeV in KIPT

Iryna S. Timchenko[1,2], O.S. Deiev[2], S.N. Olejnik[2], S.M. Potin[2], V.A. Kushnir[2], V.V. Mytrochenko[2], S.A. Perezhogin[2], A. Herzáň[1]

[1] *Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*

[2] *NSC "Kharkov Institute of Physics and Technology", National Academy of Sciences of Ukraine, 61108 Kharkiv, Ukraine*

Experimental data on photonuclear reactions in the energy range above the giant dipole resonance (GDR) and up to the pion production threshold are of particular interest for many fields of science and technology. However, the lack of such data for multiparticle reactions and discrepancies in photoneutron reaction cross-sections led to work on the analysis of the reliability of previously measured experimental data [1], and gave motivation to new experiments [2-4].

This work has presented the results of experimental study of multiparticle photonuclear reactions on ^{93}Nb, ^{181}Ta, and ^{27}Al nuclei at end-point energy of bremsstrahlung spectrum $E_{\gamma\max}$ up to 100 MeV. The experiments were performed at the electron linear accelerator LUE-40 [5] of the NSC "Kharkov Institute of Physics and Technology", the National Academy of Sciences of Ukraine. To obtain experimental flux-average cross-section $\langle\sigma(E_{\gamma\max})\rangle$, γ activation and off-line γ-ray spectroscopy were used. The modeling of bremsstrahlung flux that fell on target was performed using the GEANT4.9.2 code with taking into account the actual geometry of the experiment and the energy distribution in the electron beam, and additionally monitored by the yield of the $^{100}\mathrm{Mo}(\gamma,n)^{99}\mathrm{Mo}$ reaction.

The obtained cross-sections $\langle\sigma(E_{\gamma\max})\rangle_{\mathrm{exp}}$ were compared with experimental results from other laboratories and theoretical flux-average cross-sections $\langle\sigma(E_{\gamma\max})\rangle_{\mathrm{th}}$, which were calculated using the cross-section $\sigma(E)$ values from the TALYS code [6].

References

[1] V.V. Varlamov *et al.*, Eur. Phys. J. **A50** (2014) 114.
[2] T. Kawano, Y.S. Cho, P. Dimitriou, *et al.*, Nucl. Data Sheets **163** (2020) 109.
[3] O.S. Deiev *et al.*, Phys. Rev. **C106** (2022) 024617.
[4] H. Naik *et al.*, J. Radioanal. Nucl. Chem. **324** (2020) 837.
[5] M.I. Aizatskyi, *et al.*, Probl. Atom. Sci. Tech. **3** (2014) 60.
[6] A.J. Koning and D. Rochman, Nucl. Data Sheets **113** (2012) 2841.

Isomerism in Au isotopes

Martin Venhart[1]

[1] *Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia*

TBA

Is the X17 boson mediator of nuclear force ?

Martin Veselský[1]

[1] *Institute of Experimental and Applied Physics, Czech Technical University, 11000 Prague, Czechia*

Observation of a 17 MeV bosonic particle was first reported in 2016 by the group from ATOMKI Debrecen, Hungary [1]. Possible explanations ranged from fifth fundamental interaction to dark matter particle. We present an explanation based on cluster structure of highly excited and de-facto unbound states of light nuclei like ^{4}He, ^{8}Be and ^{12}C. The 17 MeV bosonic particle can be explained as a mediator of nuclear force between nucleons and clusters at large distances [2] . Supporting quantitative arguments could be provided by instanton theory of QCD vacuum. Such explanation can be further supported by some details of spectroscopy of light nuclei like ^{5}He and ^{5}Li. With admixture of such particle into relativistic mean field theory we generated universal equations of state which satisfy constraints from heavy ion collisions, neutron stars and also width of neutron skin of ^{208}Pb [3].

References

[1] A.J Krasznahorkay *et al.*, Phys. Rev. Lett. **116** (2016) 042501.
[2] M. Veselský, V. Petousis, J. Leja, J. Phys. G Nucl. Part. Phys. **48** (2021) 105103.
[3] M.Veselský, V.Petousis, J.Leja, L. Navarro, Symmetry **15** (2023) 49.

Muonic atom spectroscopy with radioactive targets

Stergiani M. Vogiatzi[1] **for the muX collaboration**
[1] *Paul Scherrer Institut, Villigen, Switzerland*

An ongoing experiment, pursued by the muX collaboration at Paul Scherrer Institute (PSI), aims to determine the nuclear charge radii of heavy radioactive elements such as ^{226}Ra and ^{248}Cm by means of muonic atom spectroscopy. A muonic atom is formed when a negatively charged muon stops and is captured by the surrounding nuclei in a target. The muon cascades from a high orbit to the ground state of the atom by emitting x rays. Due to its mass, the muon experiences considerably stronger binding energies compared to the electron with the low-lying muonic wave functions largely overlapping with the nuclear charge distribution. These muonic energy levels are therefore highly sensitive to the nuclear structure details and the measurement of the muonic x-ray transitions serves as a sensitive probe of the nuclear charge distribution parameters, enabling the extraction of properties such as the charge radius and the quadrupole moment.

Muonic atoms have been used in the past to determine the nuclear charge radii of almost all stable elements. With the rhenium nucleus being the only exception and demonstrating similarly high deformation as radium and curium, the measurement of the isotopically pure ^{185}Re and ^{187}Re targets was conducted in 2016 prior to the measurement of the radioactive isotopes. The analysis of the hyperfine $5 \rightarrow 4$ muonic transitions led to the extraction of the rhenium spectroscopic quadrupole moments [1]. Work in ^{185,187}Re on extracting its charge radius based on the 2p $\rightarrow$ 1s hyperfine transitions is ongoing.

PSI regulations applying to highly radioactive targets restrict their usage to microgram quantities where the direct muon capture approach cannot be implemented anymore. A technique to transfer muons to such small quantities of target material has been developed by the muX collaboration employing muon transfer reactions in a high-pressure hydrogen/deuterium gas mixture. This method allowed the measurement of the ^{226}Ra and ^{248}Cm isotopes in 2019. Although no clear indication of the radium 2p $\rightarrow$ 1s transitions is observed, we are close to determining the nuclear charge radius in ^{248}Cm, making it the heaviest element measured using muonic atoms. The status of the muX experiment is presented in this contribution.

References

[1] A. Antognini *et al.*, Phys. Rev. C **101** (2020) 054313.

Emergence of Simple Patterns in Nuclear Structure and Mixing of These Structures

John L. Wood[1]

[1]*School of Physics, Georgia Institute of Technology, Atlanta, Ga 30332-0430, USA*

We rely on recognition of simple patterns for making major steps forward in physics. Recall Keplerian orbits, Balmer line spectra, pulsar frequencies. Nuclear structure has its own special patterns, recall magic shell numbers, quadrupole moments, energies of first excited states in even-even nuclei, electric quadrupole transition probabilities.
However, over the past seven decades most of nuclear structure has seemed to get ever more complex. There have been a few modest patterns that have emerged such as intruder-state parabolas and associated shape coexistence; but overwhelmingly, complexity has appeared to escalate. Theoretical advances have appeared to go towards similar complexity.
Key insights involving simple patterns in nuclear structure will be presented. These patterns suggest that nuclear structure is dominated by a few underlying structures: deformation and symmetric or asymmetric top behaviour in most nuclei; seniority (pairing-dominated) behaviour in closed shell nuclei. These patterns are modified by coexistence of these structures and mixing. It is mixing that leads to the appearance of complexity, not an intrinsic complexity.
The consequence is that some structural types, formerly believed to exist in nuclei, are now in serious doubt; following on from the existence of such structures being seriously questioned: notably low-energy quadrupole vibrations. These doubts extend to models that possess low-energy quadrupole vibrational degrees of freedom, both simply and as part of a more general view of collective motion in nuclei. None of the more complex model views of nuclei are viable substitutes for simple structures that quantum mechanically mix.

Shape coexistence studied with Coulomb excitation in the (Z=80, N$\sim$104) and (Z=48, N$\sim$60) regions

Katarzyna Wrzosek-Lipska[1] on behalf of IS563, HIL094 and LNL22.41 collaborations

[1] *Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland*

Shape coexistence, whereby nucleus exhibit different deformations in states of similar energies, began as a rare and exotic phenomenon while now is suggested to be widespread and appear in almost every nucleus. Though establishing shape coexistence is challenging and requires highly-refined experimental methods it provides one of the most demanding and stringent tests of modern nuclear theories.

The low-energy Coulomb-excitation technique represents an ideal tool to study nuclear deformations. It allows for a direct determination of electromagnetic transition matrix elements between low-lying excited states including spectroscopic quadrupole moments and signs. Those can be further analysed in terms of quadrupole invariants [1] yielding model-independent information on shape parameters of individual states. This can be applied, however, only by reaching the required level of experimental detail.

The presentation will focus on recently performed Coulomb excitation studies for nuclei from two regions of nuclear chart: (i) the neutron-deficient mercury isotopes (Z= 80, N$\sim$104), and, (ii) the stable even-even Cd isotopes near N$\sim$60 neutron mid-shell. While the former nuclei, known from the presence of strong $E0$ transitions between states with spins $I \neq 0$ [2–4], represents one of the most prominent examples of shape coexistence [5], the latter were traditionally considered as the textbook examples of harmonic vibrational nuclei [6]. However, recent experimental and theoretical findings [7–10] clearly contradict such interpretation, indicating a multishape coexistence in ^{110,112}Cd.

A detailed studies of shape coexistence in nuclei from the N$\sim$60 and N$\sim$104 regions were performed last year using Coulomb excitation. To ascertain the shapes of the states in ^{110}Cd a series of experimental campaigns were performed at HIL in Warsaw, LNL in Legnaro and ANL last year with the use of various reaction partners. Investigation of shape coexistence in ^{182}Hg were carried out at HIE-ISOLDE. This measurement benefited from the use, for the first time, of the electron spectrometer SPEDE [11] which provided direct information on intensities of conversion electrons. An overview of these experimental campaigns will be given and future perspectives will be outlined.

References

[1] K. Kumar *et al.*, Phys. Rev. Lett. **28** (1972) 249.
[2] K. Wrzosek-Lipska *et al.*, Eur. Phys. J. A **55** (2019) 130.
[3] E. Rapisarda *et al.*, J. Phys. G **44** (2017) 074001.
[4] M. Stryjczyk, PhD thesis KU Leuven (2021).
[5] K. Heyde and J.L. Wood, Rev. Mod. Phys. **83** (2013) 1467.
[6] R.F. Casten, Nuclear Structure from a Simple Perspective (Oxford Univ. Press 1990).
[7] P.E. Garrett *et al.*, Phys. Rev. C **101** (2020) 044302.
[8] P.E. Garrett *et al.*, Phys. Rev. Lett. **123** (2019) 142502.
[9] K. Wrzosek-Lipska *et al.*, Acta Phys. Pol. B **51** (2020) 789.
[10] P.E. Garrett, J.L. Wood, S.W. Yates, Phys. Scr. **93** (2018) 063001.
[11] P. Papadakis *et al.*, Eur. Phys. J. A **54** (2018) 42.

Exploring quadrupole and octupole collectivity in ^{106}Cd via unsafe Coulomb excitation

D. Kalaydjieva[1], M. Siciliano[1,2,3], Magda Zielińska[1], J.J. Valiente-Dobón[3], A. Goasduff[3], D. Bazzacco[4], G. Benzoni[5], T. Braunroth[6], N. Cieplicka-Oryńczak[5,7], E. Clément[8], F.C.L. Crespi[5,9], G. de France[8], M. Doncel[10], S. Ertürk[11], C. Fransen[6], A. Gadea[12], G. Georgiev[13], A. Goldkuhle[6], U. Jakobsson[14], G. Jaworski[3,15], W. Korten[1], I. Kuti[17], P.R. John[4,16], A. Lemasson[8], H. Li[14], A. Lopez-Martens[13], T. Marchi[3], D. Mengoni[4,16], C. Michelagnoli[8,18], T. Mijatović[19], C. Müller-Gatermann[2,6], D.R. Napoli[3], J. Nyberg[20], M. Palacz[15], R.M. Pérez-Vidal[3,12], B. Sayği[3,21,22], D. Sohler[17], S. Szilner[19], D. Testov[4,16,23]

[1] *Irfu, CEA, Université Paris-Saclay, France*
[2] *Physics Division, Argonne National Laboratory, United States*
[3] *INFN, Laboratori Nazionali di Legnaro, Italy*
[4] *INFN, Sezione di Padova, Italy*
[5] *INFN, Sezione di Milano, Italy*
[6] *Institut für Kernphysik, Universität zu Köln, Germany*
[7] *Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland*
[8] *GANIL, Caen, France*
[9] *Dipartimento di Fisica, Università di Milano, Italy*
[10] *Universidad de Salamanca, Spain*
[11] *Ömer Halisdemir Üniversitesi, Niğde, Turkey*
[12] *Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Spain*
[13] *IJC Lab, Université Paris-Saclay, France*
[14] *Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
[15] *Heavy Ion Laboratory, University of Warsaw, Poland*
[16] *Dipartimento di Fisica e Astronomia, Università di Padova, Italy*
[17] *ATOMKI, Debrecen, Hungary*
[18] *Institut Laue-Langevin, Grenoble, France*
[19] *Ruđer Bošković Institute and University of Zagreb, Croatia*
[20] *Department of Physics and Astronomy, Uppsala University, Sweden*
[21] *Ege Üniversitesi, İzmir, Turkey*
[22] *Department of Physics, Sakarya University, Turkey*
[23] *Joint Institute for Nuclear Research, Dubna, Russia*

We studied cross-section distributions as a function of scattering angle for multiple excited states in ^{106}Cd, populated via inelastic scattering on a ^{92}Mo target. The balance between Coulomb and nuclear interaction in the population of individual states was explored by comparing the experimental γ-ray yields with the predictions obtained with the GOSIA Coulomb-excitation code. We demonstrated that from such an "unsafe" Coulomb-excitation measurement it is possible to correctly evaluate reduced transition probabilities between certain low-lying states. The obtainedvalues will be discussed in the context of new SCCM calculations describingquadrupole and octupole collectivity and shape coexistence in ^{106}Cd.