EPJ Web of Conferences **123**, 02003 (2016)
Heavy Ion Accelerator Symposium 2015
DOI: 10.1051/epjconf/201612302003

Towards Superheavies: Spectroscopy of 94 < Z < 98, 150 < N < 154 Nuclei

P. Chowdhury[1,a], S. S. Hota[1], Y, Qiu[1], I. Ahmad[2], M. P. Carpenter[2], J. P. Greene[2], R. V. F. Janssens[2], T. L. Khoo[2], F. G. Kondev[2], T. Lauritsen[2], C. J. Lister[1], D. Seweryniak[2], and S. Zhu[2]

[1] *Department of Physics and Applied Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[2] *Argonne National Laboratory, Argonne, Illinois 60439, USA*

Abstract. The heaviest nuclei where excitations above the ground state can be studied lie near $Z \sim 100$. These nuclear structure studies are important testing grounds for theoretical models that aim to describe superheavy nuclei. To study the highest neutron orbitals ($150 \leq N \leq 154$), we have populated high angular momentum states in a series of Pu ($Z = 94$), Cm ($Z = 96$) and Cf ($Z = 98$) nuclei, via inelastic and transfer reactions, with heavy beams on long-lived radioactive actinide targets. Multiple collective excitation modes and structures were identified, and their configurations deduced. Quasiparticle alignments are mapped, with odd-A band structures helping identify specific orbital contributions via blocking arguments. Higher-order multipole shapes are observed to play a significant role in disentangling competing neutron and proton alignments. The $N > 152$ data provide new perspectives on physics beyond the $N = 152$ sub-shell gap.

1 Introduction

The structure of nuclei that lie at the edges of stability in the nuclear landscape hold the most discovery potential for new physics. While nuclei along the proton and neutron drip-lines reveal stellar nucleosynthesis pathways, very heavy high-Z nuclei, whose fragility stems from enhanced Coulomb repulsion, lead us towards superheavy physics. The island of superheavy nuclei predicted to lie at the next doubly magic proton and neutron shell-gap is a topic of intense interest in contemporary nuclear structure research. While steady, albeit slow, progress is being made towards synthesising superheavy elements, their picobarn production cross-sections via fusion preclude the possibility of studying excitations built on them for some time to come. The heaviest nuclei where such spectroscopy is possible lie near $Z \sim 100$ [1], where the nuclei exhibit surprisingly robust fission barriers up to high angular momenta [2]. These studies provide critical input for constraining theoretical models that attempt to describe the physics of superheavy nuclei, which include single-particle energies, shell gaps and pairing. While $Z \geq 100$ nuclei can be produced and studied via fusion-evaporation reactions, we have concentrated on $Z < 100$ nuclei, where inelastic and transfer reactions are possible, as these are the heaviest long-lived radioactive nuclei which can be used as targets. Compared to fusion reactions leading to $Z \geq 100$, inelastic and transfer reactions with $Z < 100$ nuclei have comparatively higher cross-sections, and can populate more neutron-rich nuclei. We have focused on studying the highest neutron orbitals with $150 \leq N \leq 154$. These studies follow on the successes of prior investigations in this region using similar techniques [3–5].

2 Experiments

In a series of experiments, we have populated high angular momentum states in a range of nuclei: $^{244-246}$Pu ($Z = 94$), $^{245-250}$Cm ($Z = 96$) and $^{248-251}$Cf ($Z = 98$). Beams of ^{207,208}Pb and ^{209}Bi from the ATLAS accelerator facility at Argonne were used to bombard backed radioactive targets of ^{244}Pu, ^{248}Cm and $^{249-251}$Cf, with beam energies ~15% above the Coulomb barrier. The gamma rays were detected by ~100 Compton-suppressed Ge detectors of the Gammasphere array. The radioactive targets were deposited on a ~50-mg/cm^2 ^{197}Au backing and sealed with a thin (~150 μg/cm^2) layer of Au in front. The target activity and strong Coulomb excitation of the Au backing pose considerable experimental challenges in optimising and monitoring beam-on-target conditions. Extracting the relevant spectra from this overwhelming background required the full power of the array, both in solid angle and granularity, to extract spectroscopic information.

To illustrate this point, a summed spectrum of double-coincidence gates on transitions in the ground state band of the target nucleus ^{244}Pu is first compared in Fig. 1 to the ungated total projection of the γ-γ-γ cube. In this case, the ^{244}Pu target activity was low (≈1 nCi), and the total projection spectrum is dominated by the Coulomb excitation of the Au backing. The transitions in the ground state band are observed to be in coincidence with Pu X rays as well as the 2615-keV $2^+ \rightarrow 0^+$ transition of the reaction beam partner ^{208}Pb. These coincidences help confirm the assignment of this rotational band to ^{244}Pu. Figure 2 shows the

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[a] e-mail: partha_chowdhury@uml.edu

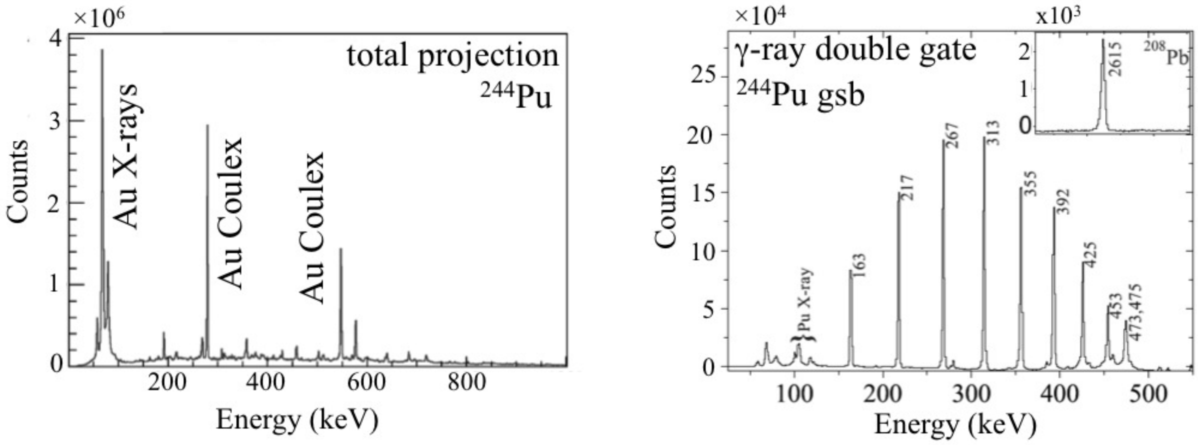

Figure 1. The total projection of a γ-γ-γ cube versus a spectrum double-gated on ground state band γ rays in ^{244}Pu (see text).

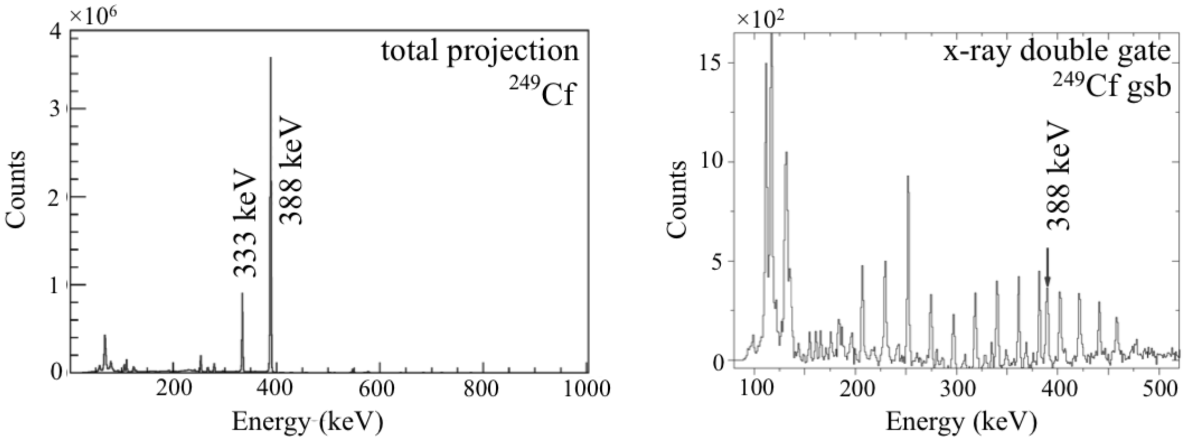

Figure 2. The total projection of a γ-γ-γ cube from the ^{249}Cf experiment versus a spectrum double-gated on Cf X rays (see text).

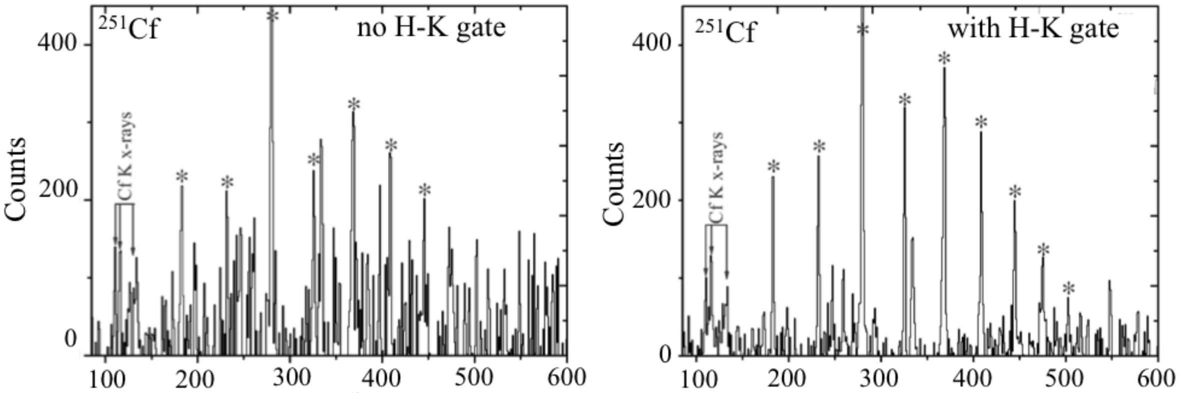

Figure 3. Comparison of ^{251}Cf spectra without and with H-K gating, demonstrating vastly improved signal-to-noise ratios (see text).

total projection of a γ-γ-γ cube for the ^{249}Cf target with an activity of ≈25 μCi, where the spectrum is now dominated by ^{245}Cm γ rays from the α decay of ^{249}Cf. Here, a double gate on two Cf X rays suppresses the Cm γ rays and reveals the ground state band in ^{249}Cf. Finally, Fig. 3 illustrates how gating on sum-energy (H) and gamma-ray fold (K) helps remove fission background contributions in the case of ^{251}Cf without affecting the photopeak intensities.

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3 Results

Rotational excitations were populated typically to angular momenta $I > 20\hbar$ in all nuclei, with multiple band structures identified and quasiparticle alignments mapped in each nucleus [6, 7]. A couple of key experimental highlights and physics advances are briefly summarised below.

3.1 N = 151 nuclei

Band structures in odd-A nuclei help identify specific nucleon orbitals on which the rotations are built. Prior to the present work, for $N = 151$ nuclei, there was only limited spectroscopic information for ^{245}Pu [8], with only ground-state bands observed in ^{247}Cm and ^{249}Cf [9]. We have now identified two rotational band structures in ^{245}Pu built on the $\nu[734]9/2^-$ and $\nu[624]7/2^+$ configurations, as well as new rotational bands in ^{247}Cm and ^{249}Cf built on the $\nu[622]5/2^+$ configuration [6]. In each case, the configurations are deduced experimentally through measured $M1/E2$ branching ratios between the signature partners. This is the first time high-spin rotational bands built on both ground and excited state configurations, especially on orbitals other than the $j_{15/2}$ neutron orbital, have been identified and characterised in $N > 150$ systems. A long-standing unresolved issue in the $A \sim 250$ region is the fact that the expected early alignment of the $j_{15/2}$ neutrons from cranked Woods-Saxon predictions is not observed [9, 10], while the alignment of $i_{13/2}$ protons, typically predicted to occur at frequencies higher than the neutrons, has been fully mapped, e.g, in ^{244}Pu [4]. The identification of collective bands built on different configurations in the $N = 151$ isotones of Pu, Cm and Cf now allow competing alignment contributions from neutrons and protons to be disentangled using blocking arguments [6].

In ^{245}Pu and ^{247}Cm, both bands, built on different neutron orbitals, track the alignment upbends at the same frequency as their even-even ^{244}Pu and ^{246}Cm cores, respectively. Since the $j_{15/2}$ neutron alignment is blocked for the ground state $\nu[734]9/2^-$ configurations in both cases, the data suggest a common proton pair alignment. In ^{249}Cf, the $\nu[734]9/2^-$ ground state band again tracks the flat behaviour of the ^{248}Cf core, while the $\nu[622]5/2^+$ band (in which the $j_{15/2}$ neutron alignment is not blocked) shows a slight uptick and overtakes the flatter ground state band curve at the highest frequencies observed [6].

Since effects of higher order shape multipoles, especially β_6 deformation, have been reported to be significant in this mass region [11], we performed cranked Woods-Saxon calculations with and without β_6 for these $N = 151$ isotones. The predicted alignment frequencies with and without β_6 deformation are compared to experimental data in Fig. 4. The predicted proton alignment frequencies are seen to be reduced by ≈0.03 MeV in ^{245}Pu with the inclusion of β_6, while increasing the neutron alignment frequencies by ≈0.015 MeV at the same time. Without the inclusion of β_6, for all the three $N = 151$ nuclei studied, the neutrons are predicted to align earlier than the protons, contrary to experimental observations. The inclusion of this higher order shape multipole flips the order of the neutron and proton alignments in ^{245}Pu and ^{247}Cm, thus effectively bringing experiment and predictions in line for proton and neutron alignments in these nuclei (see Ref.[6] for more details).

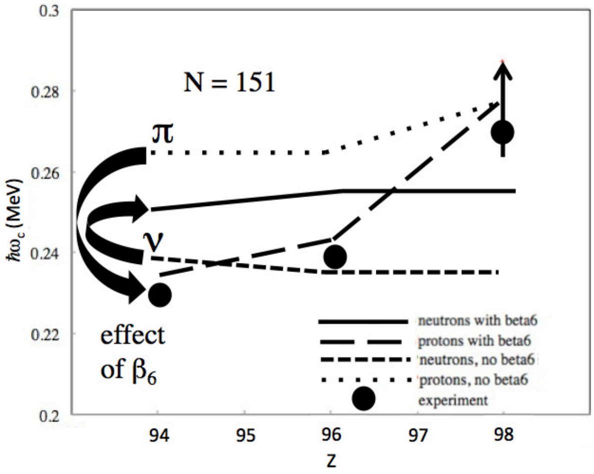

Figure 4. Effect of β_6 on neutron and proton crossing frequencies.

3.2 N > 152 nuclei

We have investigated the $N = 153$ nucleus ^{251}Cf and established the ground state band built on the $\nu[620]1/2^+$ orbital to J^π=45/2$^+$ [12]. A comparison of the alignment behaviour of ^{251}Cf with its neighbouring lighter $N = 153$ isotone ^{249}Cm [9] shows that the two align at frequencies that differ by ≈0.03 MeV, precluding a neutron alignment scenario and endorsing a proton alignment behaviour for both nuclei.

Finally, we have studied the $N = 154$ nucleus ^{250}Cm and extended the ground state band, observed earlier to J^π=12$^+$ [13], to J^π=24$^+$ [7]. This is the first even-even nucleus beyond the $N = 152$ shell gap that is studied to high angular momenta. A strong alignment upbend is observed at the highest frequencies, in contrast to the neighbouring lighter even-Cm isotopes. This, together with a reduced kinematic moment of inertia at low spins for the $N = 154$ isotope compared to its neighbours, points towards increased pairing correlations beyond the $N = 152$ sub-shell gap. The sharp alignment feature also provides a tantalising possibility that the crossing may involve high-j low-Ω orbitals that originate from above the $N = 184$ spherical shell gap, but have been brought down by deformation to the valence region near $N = 154$ [7, 14].

3.3 Summary and Outlook

Our experimental program with inelastic and transfer reactions with heavy beams and radioactive actinide targets using the Gammasphere array has yielded a wealth of new data in $94 < Z < 98$ nuclei. These have expanded our spectroscopic horizons in this very heavy mass region to high angular momenta, allowed us to study collective excitations built on the highest neutron orbitals, and have served as an excellent complement to the fusion-evaporation studies of excitations in $Z > 100$ nuclei [1]. Expanding the studies to odd-Z nuclei is a natural next step for a comprehensive exploration of the $N - Z$ landscape, as very little data exists in that domain. We are currently pursuing vibrational excitations and non-axial shape degrees of freedom in this mass region from the prompt spectroscopy. Finally, K-isomer studies remain a rich hunting ground, not only to extract single-particle energies and address pairing correlations, but to explore whether and how these metastable states that arise from quantum hindrances can inform our understanding of the stability and synthesis of superheavy elements.

Acknowledgments

We gratefully acknowledge helpful discussions with our theoretical colleagues Stefan Frauendorf and Furong Xu. The trans-plutonium element production facilities at Oak Ridge National Laboratory, supported by the Office of Basic Energy Science, U.S. Department of Energy, are acknowledged for providing isotopes for the targets. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under award numbers DE-FG02-94ER40848 and contract number DE-AC02-06CH11357. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science user facility.

References

[1] Ch. Theisen *et al.*, Nucl. Phys. **A944**, 333 (2015).
[2] G. Henning *et al.*, Phys. Rev. Lett. **113**, 262505 (2014).
[3] G. Hackman *et al.*, Phys. Rev. C **57**, 1056(R) (1998).
[4] I. Wiedenhoever *et al.*, Phys. Rev. Lett. **83**, 2143 (1999).
[5] K. Abu Saleem, Ph.D. Thesis, Illinois Institute of Technology, (2002).
[6] S. S. Hota *et al.*, Phys. Lett. B **739**, 13 (2014).
[7] S. S. Hota, Ph.D. Thesis, University of Massachusetts Lowell, (2012).
[8] H. Makii *et al.*, Phys. Rev. C **76**, 061301(R) (2007).
[9] S. K. Tandel *et al.*, Phys. Rev. C **82**, 041301(R) (2010).
[10] K. Abu Saleem *et al.*, Phys. Rev. C **70**, 024310 (2004).
[11] A. Sobiczewski *et al.*, Phys. Rev. C **63**, 034306 (2001).
[12] Y. Qiu *et al.*, to be published.
[13] T. Ishii *et al.*, J. Phys. Soc. Japan **75**, 043201 (2006).
[14] S. S. Hota *et al.*, to be published.