# Probing the Low-lying Level Structure of $^{94}$Zr Using $\beta^-$ decay

K. Mandal[1], H. Sultana[1], A. Chakraborty[1,2,3],* E.E. Peters[3], B.P. Crider[2], C. Andreoiu[4], P.C. Bender[5], D.S. Cross[4], G.A. Demand[6], A.B. Garnsworthy[5], P.E. Garrett[6], G. Hackman[5], B. Hadinia[6], S. Ketelhut[5], Ajay Kumar[2,3], K.G. Leach[6], M.T. McEllistrem[2], J. Pore[4], F.M. Prados-Estévez[2,3], E.T. Rand[6], B. Singh[7], E.R. Tardiff[5], Z.-M. Wang[4,5], J.L. Wood[8], and S.W. Yates[2,3]

[1]*Department of Physics, Siksha Bhavana, Visva-Bharati, Santiniketan, West Bengal 731 235, India*
[2]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[4]*Department of Chemistry, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*
[5]*TRIUMF, University of British Columbia, Vancouver, British Columbia V6T 2A3, Canada*
[6]*Department of Physics, University of Guelph, Guelph, Ontario, N1G 2W1, Canada*
[7]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4L8, Canada and*
[8]*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA*

## Introduction

The structural evolution along the chain of even-A Zr isotopes is shown in Fig. 1. It is evident from the figure that there is a major shape transition with increasing neutron number from spherical $^{90}$Zr to strongly deformed $^{102}$Zr. The lightest stable isotope, $^{90}$Zr, lies at the $N = 50$ shell closure, whereas the heaviest stable isotope, $^{96}$Zr, lies at the $N = 56$ subshell closure. Lying between these two closures, $^{92,94}$Zr appear to have spherical ground states. It is also observed that there is an onset of mild collectivity in $^{94}$Zr at the excitation regime of $\sim$1.3 − 1.7 MeV. The excitation of protons across the $Z = 40$ subshell closure appears to play a dominant role in stabilising the collective structure in $^{94}$Zr in this low-energy regime [1]. We are reporting here a part of our findings for $^{94}$Zr obtained from an experiment following $\beta^-$ decay of $^{94}$Y.

*Electronic address: `anagha.chakraborty@visva-bharati.ac.in`

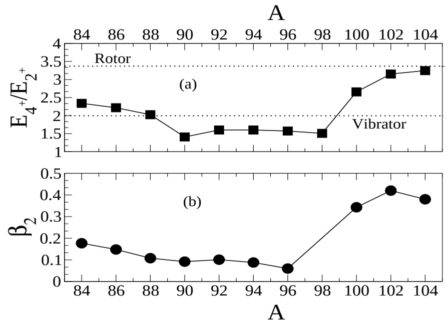


FIG. 1: Evolution of the low-lying level structure of even-even Zr isotopes. Variation of (a) the ratio between the level energies of the first $4^+$ and $2^+$ states and (b) the quadrupole deformation parameter, $\beta_2$, as a function of mass number, A.

## Experimental Procedures and Results

The low-lying excited states of $^{94}$Zr were populated through $\beta^-$ decay of radioactive $^{94}$Y ($T_{1/2}$ = 18.7 min, $J^\pi = 2^-$, $Q_{\beta^-}$ = 4.918 MeV and 100% $\beta^-$ branch). The experiment was carried out at the TRIUMF Isotope Separator and Accelerator radioactive beam facility. The accelerated 500 MeV proton beams impinged upon a $^{238}$UCx target and the radioactive $^{94}$Y sources were produced as fission fragments. Following mass separation of the fission products, $A = 94$ mass activities were deposited on the moving tape collector at the center of the $8\pi$ spectrometer. This spectrometer was comprised of an array of 20 Compton-suppressed HPGe detectors along with other detection devices for charged particles. The details of the experimental setup can be found in Ref. [1]. For off-line analysis, standard $\gamma$-ray spectroscopic techniques were used. The random-background-subtracted $\gamma - \gamma$ coincidence matrix contained about $2\times10^8$ events. Representative singles spectra showing the high-energy region are depicted in Fig. 2. Combining the singles and coincidence data, a comprehensive level scheme of $^{94}$Zr has been constructed up to $E_x = 4.8$ MeV, which is very close to the $Q_{\beta^-}$ value. A total of 64 new levels and 161 new transitions has been placed in the decay scheme of $^{94}$Zr. Several weak and low-energy decay branches have been newly placed from previously known levels, and the corresponding $B(E2)$ values could be obtained using the lifetimes of the levels from Ref. [2]. It appears that none of these transitions carry significant $E2$ strength, except for the 371 keV ($2_2^+ \rightarrow 0_2^+$)-transition, thereby suggesting the dominance of single-particle excitations. For theoretical interpretation of the observed structure in $^{94}$Zr, shell model calculations were carried out using the NuShellX code [3]. $^{88}_{38}$Sr$_{50}$ was used as the inert core and the valence space was comprised of $\pi(2p_{1/2}, 1g_{9/2})$ and $\nu(3s_{1/2}, 2d_{5/2})$ configurations. The two-body interaction matrix file "*gl*" was used for the calculation. Reasonable agreement between the experimental and theoretical level energies was obtained (see Fig. 3). It is observed that the wave function structure of the first and second $0^+$ states is quite different. A neutron pair excitation from $3s_{1/2} \rightarrow 2d_{5/2}$ is the dominant contribution to the wave function of the $0_1^+$ state. On the other hand, for the $0_2^+$ state, a proton pair excitation from $2p_{1/2} \rightarrow 1g_{9/2}$ dominates the wave function.

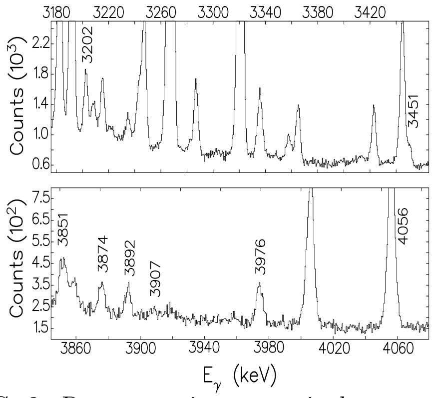


FIG. 2: Representative $\gamma$-ray singles spectra for $^{94}$Zr showing the higher-energy regions. The ground state transitions are labelled with their energies. The unmarked $\gamma$ rays are the ones feeding the first three excited states of $^{94}$Zr.

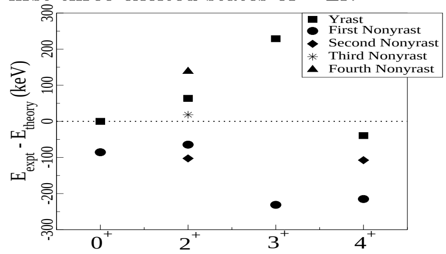


FIG. 3: Difference between experimentally observed and shell model predicted level energies for a few of the low-lying states of $^{94}$Zr.

## Acknowledgments

This material is based upon work supported by the U.S. National Science Foundation under Grant No. PHY-1606890. K. Mandal would like to thank IUAC, New Delhi for financial support through Project Code No. UFR-56317. H. Sultana and A. Chakraborty would like to thank UGC-DAE CSR, Kolkata for financial support through Project No. UGC-DAE-CSR-KC/CRS/13/NP04/02.

## References

[1] A. Chakraborty *et al.,* Phys. Rev. Lett. **110**, 022504 (2013).

[2] E. Elhami *et al.,* Phys. Rev. C **78**, 064303 (2008); E. Elhami *et al.,* Phys. Rev. C **88**, 029903 (2013).

[3] www.nscl.msu.edu/ brown/nushell.zip