NUCLEAR THEORY, Vol. 41 (2024)
eds. M. Gaidarov, N. Minkov, Heron Press, Sofia

Something from Nothing: The γ-Ray Spectroscopy of ^{231}U

D.G. Roux[1], **R.A. Bark**[2], **E.A. Lawrie**[2,3], **J.J. Lawrie**[2],
S.S. Ntshangase[4], **T.S. Dinoko**[2], **J.L. Easton**[2], **P. Jones**[2],
B.V. Kheswa[3], **N.A. Khumalo**[3], **S.N.T. Majola**[2,5], **L.P. Masiteng**[2,5],
D. Negi[2,6], **S.P. Noncolela**[2,3,7], **J.F. Sharpey-Schafer**, **O. Shirinda**[2],
P.C. Uwitonze[1,8]

[1]Department of Physics and Electronics, Rhodes University, 6140 Grahamstown, South Africa
[2]iThemba LABS, National Research Foundation, P. O. Box 722, Somerset West 7129, South Africa
[3]University of the Western Cape, Department of Physics, Private Bag X17, Bellville 7535, South Africa
[4]University of Zululand, Department of Physics, Private Bag X1001, KwaDlangezwa 3886, South Africa
[5]Department of Physics, University of Johannesburg, P. O. Box 524, Auckland Park 2006, South Africa
[6]Department of Physics, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka- 576104, India
[7]University of Stellenbosch, Department of Physics, Stellenbosch, South Africa
[8]University of Rwanda, Department of Mathematics, Sciences and Physical Education, 50 Rwamagana, Rwanda

Abstract. The γ-ray spectroscopy of uranium nuclei far from stability is complicated by competition from electron conversion and large fission cross sections. We observed the first rotational bands in ^{231}U in the ^{232}Th(α,5n) reaction at a beam energy of 52 MeV by using the AFRODITE γ-ray spectometer array in conjunction with a recoil detector to discriminate against the fission background. The data revealed three rotational bands, interpreted as the ground-state band $\nu[633]5/2^+$, yrast band $\nu[752]5/2^-$, and an excited band $\nu[631]3/2^+$. The configuration assignments are supported by Cranked Shell Model calculations and the electromagnetic properties of the bands. The excitation energy of the $\nu[752]5/2^-$ band head is suggested to be 113.0 keV. Uranium-231 is currently the lightest odd-A uranium nucleus shown to exhibit collective structure.

1 Introduction

This paper highlights several interesting problems we encountered while building the ^{231}U level scheme from a sparse data set, and how these were addressed. A comprehensive report may be found in reference [1]. We performed a series of three experiments involving ^{232}Th(α,xn) reactions in a campaign to search for broken symmetries in the $A \simeq 230$ mass region. The first two employed beam energies of 42 and 61 MeV [3], chosen to maximize the yields of ^{232}U and ^{230}U, respectively. After the 61-MeV data had revealed several unknown bands in coincidence with the uranium X-rays, we decided to run a third experiment at an intermediate beam energy, 52 MeV, in order to confirm whether the new bands might belong to ^{231}U. The extended data set from all three experiments indicated that the bands are indeed associated with ^{231}U. To date this is the lightest uranium isotope shown to support rotational band structures.

The experiments employed the AFRODITE spectrometer array, which included nine suppressed Clovers, operated in coincidence with a recoil detector. The pulsed α-particle beams were provided by the K=200 iThemba LABS Separated Sector Cyclotron [1].

2 Level Scheme

Although the extended data contained several different uranium isotopes with mass numbers from 230 to 234, we could assign the new bands to ^{231}U by comparing the experimental yields across three different beam energies, as described in reference [1]. Figure 1 shows the new structures associated with ^{231}U, labelled Bands 1, 2 and 3. They were constructed according to γ-γ coincidence relationships and intensities, using Radware [2]. All of the bands are floating and comprise pairs of signature partners. Band 1 is the strongest, followed by Band 2 and Band 3.

Band 1 differs from the others in that it is the only case where the signature partners could be linked by (two) observed ΔI=1 linking transitions. The band is associated with the lowest-energy configuration, predicted by Cranked Shell Model (CSM) calculations to be $[752]5/2^-$. It is also predicted to exhibit significant signature splitting of $\sim$60 keV, which is consistent with the measured value.

A pair of decay sequences is associated with the second strongest Band 2, which is assigned the next lowest configuration, $[633]5/2^+$. In spite of the absence of observed ΔI=1 linking transitions between the decay sequences, the fact that CSM predicted almost zero signature splitting for this orbital was used to infer that they must be signature partners. For bands with zero splitting, the E2 transition energy in one signature partner is the average of those in the opposite signature,

$$E_{\mathrm{E2}}(I) \simeq \frac{1}{2}\left[E_{\mathrm{E2}}(I+1) + E_{\mathrm{E2}}(I-1)\right],$$

where $E_{\mathrm{E2}}(I)$ represents the energy of the stretched E2 transition from the state with spin I, for example. It turns out that this equation describes the observed transition energies in the proposed signature partners with an average error of less than 0.3%. For this reason we assumed that the decay sequences grouped in this band are indeed partner bands.

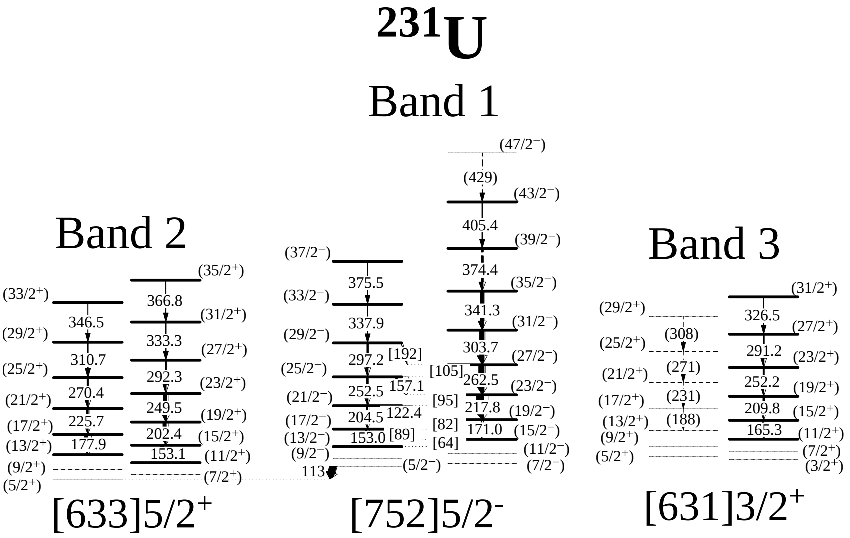

Figure 1. New rotational bands in ^{231}U. States observed in our data appear as bold horizontal lines, and tentative levels as dashed lines, with the lowest levels extrapolated. The arrow widths reflect the γ-ray intensities. Tentative spin-parity values and tentative transitions appear in parentheses. Crossover $\Delta I = 1$ transitions which were not observed, but inferred from intensity balances, are enclosed in square brackets. The excitation energy of Band 3 is chosen to be consistent with CSM predictions. The γ-rays energies are in keV.

The weakest band, associated with the $[631]3/2^+$ configuration, is also expected to exhibit negligible splitting. Only one sequence of Band 3 was actually observed. The transitions in the second sequence were tentatively inferred by setting gates on energies predicted by the above equation. Supporting spectra for all the bands are shown in reference [1].

The tentative spin values were assigned by using the CSM predicted alignments as a guide.

3 Something from Nothing

The competition from fission and electron conversion both conspired to produce a data set with low statistics.

We discriminated against the fission background by coupling the AFRODITE array to a recoil detector situated downstream from the target [1]. The recoil detector measures the time of flight of reaction products from the target to itself. It generates a corresponding time signal, allowing one to discriminate between γ-rays associated with the unwanted fast fission fragments and those emitted by the much slower recoiling residual nuclei of interest. A γ-γ matrix was constructed by demanding a coincidence between the recoil detector time signal and at least two of the Clovers. When the 52-MeV experiment was run in the recoil-γ-γ coincidence mode, the event rate was reduced by a factor of $\sim$100, to an average of about 30 Hz. Even after five weekends of acquisition the statistics were poor. In addition to this there was the problem of electron conversion.

Both the ΔI=1 linking and the in-band ΔI=2 transitions are strongly converted in the actinide nuclei. The reasons for this are the $\sim Z^3$ dependence of the conversion coefficient α_T, and the fact that E2 rotational transitions in the large-moment-of-inertia actinides have low energies when compared with nuclei of lower mass number. Low-energy transitions are also the most strongly converted. Transitions in the lower part of uranium bands are expected to have energies of $\sim$100 keV, as shown in Figures 1 and 3. If we consider a 100-keV transition as an illustrative example, the conversion coefficients for the two most likely multipolarities are $\alpha_T(\mathrm{E2}) = 14$ and $\alpha_T(\mathrm{M1}) = 5$ [4]. This means that only 6% of E2 and 17% of M1 intensity proceeds via γ-decay, the remainder being converted. For the lowest E2 transitions in a band, expected to have energies of $\sim$ 50 keV, only 0.2% can be expected to proceed via γ-decay, and there is no hope of seeing them at all. It is therefore understood that many of the γ-rays did not rise above background in the gated spectra.

With this in mind, let's have a look at some of the challenges in constructing a level scheme from data with poor statistics.

The fitted intensities of Band 1 suggested that the prominent 113-keV transition has E1 ($\alpha_T = 0.09$) rather than E2 ($\alpha_T \sim 9$) character. The 113-keV gated spectrum (Figure 2) shows both signatures, but we encountered two interesting puzzles when constructing this band. Firstly, although we did find two $\Delta I = 1$ linking transitions connecting the $\alpha = +1/2$ to the the $\alpha = -1/2$ partner, we did not observe any in the opposite direction, and secondly, when we set a gate on 304 keV in the $\alpha = -1/2$ signature, the 171-keV transition was hardly visible at all. This may be seen in Figure 3, panel (a). Panel (b) shows a gate on a matching transition (306 keV) in the neighbouring nucleus ^{232}U, for comparison. As

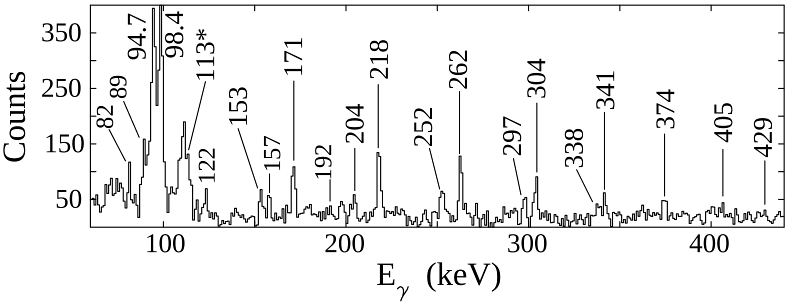

Figure 2. Coincidence spectrum for Band 1, gated on the 113-keV transition near the bottom of the band. The 98.4 and 94.7-keV uranium Kα X-rays are clearly visible. The gating transition is labelled with an asterisk.

expected for a single decay sequence, there is no sudden loss of intensity in the corresponding 166-keV transition in that nucleus. How then does the $\alpha = -1/2$ band lose intensity between the 304-keV and the 171-keV transitions, if there are no $\Delta I = 1$ out-of-band decay pathways?

It it likely that such pathways do exist. We therefore inserted the "missing" $\Delta I = 1$ transitions (shown in square brackets in Figure 1) on the assumption that they are present, but strongly converted, and therefore not observed. The assigned intensities were based on model-dependent branching ratios, which were calculated in the following way.

First, the theoretical reduced transition rates $B(\mathrm{M1})$ and $B(\mathrm{E2})$ were calculated using the rotational model,

$$\begin{aligned} B(\mathrm{M1}) &= \frac{3K^2}{4\pi}\left(g_K - g_R\right)^2 \langle I_i K 10 | I_f K\rangle^2, \\ B(\mathrm{E2}) &= \frac{5}{16\pi} Q_0^2 \langle I_i K 20 | I_f K\rangle^2. \end{aligned} \tag{1}$$

The parameters g_K and g_R are the gyromagnetic ratios for the intrinsic state and the collective motion of the core, and Q_0 is the quadrupole moment. A discussion of the values used for these parameters may be found in [1].

Next, the theoretical branching ratios λ were extracted using the standard expression

$$\frac{B(\mathrm{M1})}{B(\mathrm{E2})} = 0.697 \frac{E_2^5}{E_1^3} \frac{1}{\lambda(1+\delta^2)} \frac{\mu_N^2}{e^2 b^2},$$

where $\lambda = T_2/T_1$ is the ratio of the respective γ-ray intensities of $\Delta I = 2$ and $\Delta I = 1$ transitions, and E_2 and E_1 are the energies of the $\Delta I = 2$ and $\Delta I = 1$ transitions in MeV. The mixing ratio $\delta^2 = T_1(\mathrm{E2})/T_1(\mathrm{M1})$ was assumed to be zero.

Once the branching ratios had been established for the transitions below the $(27/2^-)$ level, and the unobserved $\Delta I = 1$ linking transitions had been included in the decay scheme, a gate was set on the 304-keV transition, which feeds the $(27/2^-)$ level. A theoretical gated spectrum was then generated by adjusting only one free parameter, the intensity of the gating transition. The calculated spectrum predicts the pattern of intensities in the lower part of Band 1 very well, as may be seen in upper panel of Figure 3, where it is superimposed on the observed spectrum, in red. Note how the 171-keV transition almost disappears in the calculated spectrum, and how the $\Delta I = 1$, M1/E2 linking transitions are calculated not to rise above the background, consistent with the observed spectrum.

Of the three bands, Band 1 is expected to show the greatest M1 strength. It is evident from Eqn. 1 that the expected M1 strength depends strongly on the quantity $(g_K - g_R)^2 K^2$ (the Clebsch-Gordan coefficients are weak functions of I and K). We found this quantity to have the value 0.90 for Band 1, 0.01 for Band 2, and 0.29 for Band 3. See reference [1] for the details. These values are

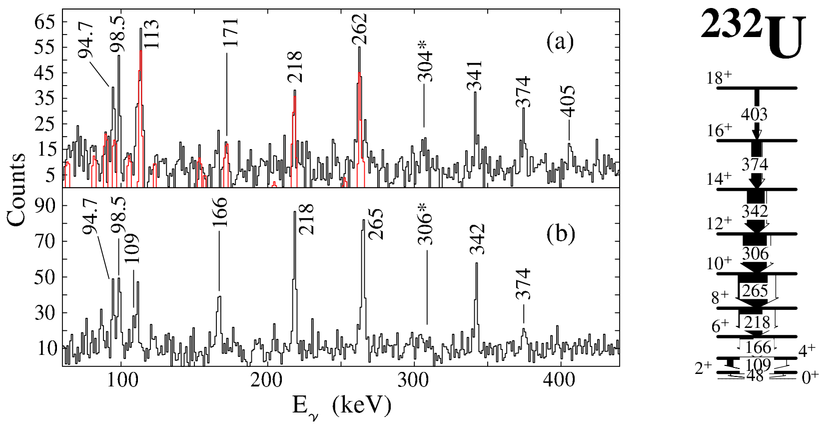

Figure 3. (Colour online) These spectra contrast the different γ-ray intensity patterns in the yrast band of ^{231}U and the neighbouring nucleus ^{232}U, which is shown on the right as a reference. Asterisks denote energy gates. Note the 98.4 and 94.7-keV uranium X-rays. (a) Coincidence spectrum gated on the 304-keV transition in ^{231}U. The simulated spectrum is shown in red. (b) Spectrum gated on the analogous 306-keV transition in ^{232}U.

consistent with the observation of dipole linking transitions in Band 1, but not the other bands.

We have thus shown that the expected electromagnetic properties of Band 1 are consistent with the presence of unobserved, strongly converted ΔI=1 transitions in the lower part of the band.

Bands 2 and 3 are considerably weaker. The spectra, shown in [1], were constructed by summing gates, which were themselves strongly converted (presumably) E2 transitions of a rotational nature. The signature partners could not be linked, due to the poor statistics and the low value for $(g_K - g_R)^2 K^2$, mentioned above.

In conclusion, we constructed three new bands in the neutron deficient nucleus ^{231}U from the sparse 52-MeV data set. Configuration assignments were based on CSM calculations, which were also used as a guide to assign tentative, model-dependent spins. The electromagnetic properties of the bands are consistent with those predicted for each intrinsic configuration. For example, we observed two ΔI=1 linking transitions in the $[752]5/2^-$ band, which is expected to show the greatest M1 strength, but none in the $[633]5/2^+$ or $[631]3/2^+$ bands, where the theoretical M1 strength is weaker. For the $[752]5/2^-$ band, a gated spectrum was calculated, assuming the presence of unobserved, highly converted ΔI=1 transitions between the signature partners. The calculated spectrum is consistent with the presence of such transitions, and the observed transition intensities in the lower part of the band. In particular, it explains the mysterious disappearance of the 171-keV peak in the gated spectrum.

References

[1] D.G. Roux et al., *Eur. Phys. J. A* **60** (2024) 118.
[2] D.C. Radford, *Nucl. Instr. Meth. A* **361** (1995) 297-305.
[3] S.S. Ntshangase et al., *Phys. Rev. C* **82** (2010) 041305 (R).
[4] T. Kibédi et al., *Nucl. Instr. Meth. A* **589** (2008) 202.