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Evidence for shape coexistence at medium spin in ^{76}Rb

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ABSTRACT

Four previously known rotational bands in ^{76}Rb have been extended to moderate spins using the Gammasphere and Microball γ ray and charged particle detector arrays and the ^{40}Ca(^{40}Ca, 3pn) reaction at a beam energy of 165 MeV. The properties of two of the negative-parity bands can only readily be interpreted in terms of the highly successful Cranked Nilsson–Strutinsky model calculations if they have the same configuration in terms of the number of $g_{9/2}$ particles, but they result from different nuclear shapes (one near-oblate and the other near-prolate). These data appear to constitute a unique example of shape coexisting structures at medium spins.

One of the remarkable properties of the nuclear quantal many body system is its ability to minimize its energy by adopting different nuclear shapes for a relatively small cost in energy compared to the total binding energy. This, coupled with the shape driving effects of the odd nucleons can, in certain circumstances, result in different nuclear shapes being possible at low excitation energies in nuclei. Recent calculations [1] have pinned down the regions of the nuclear chart where nuclei may assume different shapes at close to groundstate energies. In some cases as many as four different minima, corresponding to different shapes, are found in the potential energy surface for a single nucleus. The degree to which the groundstate wavefunction becomes a mixture of these differently shaped states or if the minima give rise to individual nuclear states is still an open and interesting question.

Various reviews have been performed over the last 20 years on shape coexistence in atomic nuclei, with the most recent being by Heyde and Wood [2]. Potentially, one of best examples of nuclear shape coexistence at low spins is found in the light lead nucleus, ^{186}Pb, where the first three excited 0^+ states are believed to result from spherical, oblate and prolate minima, respectively, in the potential energy surface [3]. This particular phenomenon of shape coexistence has been discussed in terms of intruder states based on proton particle–hole excitations across the $Z = 82$ shell gap

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[2,4,5]. The phenomenon is also known to occur at much higher spins where many excited rotational bands can often be found. Since each band is usually built on different excited configurations this often results in different shapes that can change with spin. It is however only when the states are sufficiently similar and possess the same quantum numbers that one may see an interaction between rotational bands. Such interactions can then provide information about the degree of shape mixing.

The neutron deficient nuclei with mass $A = 70$–80 are located in a region of large deformed shell gaps [6]. Strong gaps exist at both oblate $(34, 36)$ and prolate $(36, 38)$ nucleon numbers [7]. The first evidence for shape coexistence at low spins in this region was proposed in ^{72}Se [8] and a detailed review of all the early data was made by Wood et al. [4] some years later. More recently detailed studies of shape coexistence and mixing between the low-spin oblate and prolate states has been investigated in $^{72-78}$Kr [7]. The nucleus ^{76}Rb, which has 37 protons and 39 neutrons, is located in the region of interest. However, whilst ^{76}Rb does not directly possess any of the nucleon numbers where large shell gaps occur for oblate shapes, there are long standing suggestions for the presence of shape coexistence in the nucleus at low spins [9] as well as indications for evidence of the phenomenon in $N = 39$ isotopes of Ge, Se, Kr and Sr (see Fig. 38 of Ref. [2]). At moderate spins the nucleus has been found to be dominated by five very regular rotational structures [10]. In the present work these structures have been extended to spins of the order of $30\hbar$, with over 40 new γ rays being observed. The structures observed, and the interactions between them can be interpreted, with the aid of cranked Nilsson–Strutinsky (CNS) calculations, as providing evidence of an excellent example of the coexistence at moderate spins of oblate and prolate structures. Of particular interest is the fact that two bands can be interpreted as being constructed from the same basic configurations, i.e. with the same number of particles excited to the $g_{9/2}$ shell, but with very different shapes. To our knowledge, this is the first example of this kind of shape coexistence at high spin where the rotational bands in both minima are observed in an extended spin range. A further interesting feature is that it has been possible to extract approximate interaction matrix elements between the bands in the two minima at spin values $I \approx 12$ and $I \approx 20$, respectively.

The experiment was performed at the Argonne National Laboratory using the ATLAS accelerator to produce a ^{40}Ca beam at 165 MeV. This beam was used to bombard a 350 $\mu g/cm^2$ ^{40}Ca target that was flashed on both sides with 150 $\mu g/cm^2$ of gold to prevent oxidation. The reaction channel of interest in the present work was ^{40}Ca(^{40}Ca, 3pn)^{76}Rb. γ rays from ^{76}Rb were detected using the Gammasphere array [11], which consisted of 99 Compton suppressed Ge detectors, and identification of evaporated charged particles was performed using the Microball array [12]. An event was triggered on the condition of at least four of the HPGe detectors firing in prompt coincidence. A total of 1.5×10^9 high-fold events were recorded. The information from the Microball array, that provides the energies and directions of the detected charged particles, allowed for an offline event-by-event reconstruction of the momenta of the residual nuclei [13,14], thereby resulting in an improved energy resolution for the γ-ray peaks.

Events coinciding with the detection of no α particles and 1 or 2 protons were used to help select the nucleus ^{76}Rb. Attempts to enhance the channel of interest (3pn) using the 3p-gated data and the total energy plane (TEP) method [15] did not improve the signal to background significantly. This is due to the finite charged particle detection efficiencies and the strongly overlapping locations in the 3p-gated TEP of the 3pn events in which the neutron is not detected, 4p events in which one of the protons was not detected, and α3p events in which the α-particle was not detected. An open TEP gate was thus utilised in order to maximise statistics. The events, with the above particle gating conditions, were used to create a γ–γ–γ cube which was used to extend the known [10] energy level decay scheme for the nucleus. The level scheme, deduced with the aid of the RADWARE [16] graphical analysis package, is shown in Fig. 1. The spins and parities of the extended rotational structures are assigned on the assumption that the observed transitions are stretched E2's, since it was not possible to obtain sufficiently accurate directional correlation from oriented state (DCO) values to unambiguously confirm the multipolarity of the transitions.

Fig. 2 shows some partial spectra in support of the proposed level scheme and to illustrate the overall level of statistics and quality of the data. The double gating conditions used to create the spectra shown from the E_γ–E_γ–E_γ cube are described in the relevant figure captions. The present work agrees with the previous work [10] for the low spin part of the decay scheme but most bands have been extended to considerably higher spin values. The $\alpha = 0, 1$ signatures of 'band 1' with positive parity have been extended by 6 and 5 transitions, respectively. The negative parity bands are labelled as bands 3, 4 and 5 at low-spin. In the present work the even and odd spin sequences of band 3 have been extended by 5 and 8 transitions, respectively. A new sequence of 4 (plus 1 tentative) transitions with $\alpha = 1$ (band 3a′), has also been observed in the present work which feed into the original $\alpha = 1$ structure of band 3 at spin $11^{(-)}$. It is assumed that all the observed transitions in band 3a′ have E2 multipolarity. It is also interesting to note that band 3 is connected to band 5, the relevance of which will be discussed further below. Finally, band 4 has been extended by 4 (plus 1 tentative) and 5 transitions for the $\alpha = 0, 1$ signatures, respectively.

A closer study of the band structure in Fig. 1 indicates an interesting sequence of interactions between the negative parity structures. It is evident that in the $I = 20$–30 spin range, the odd spin sequence of band 3 is signature degenerate with the even spin sequence of band 4 (cf. Fig. 4 below), i.e. these two sequences must be signature partners which is in contradiction to the band assignment at low spin according to Ref. [10] and as drawn in Fig. 1. Furthermore, the odd spin sequences of bands 3 and 4 interact around $I = 20$ with connecting transitions which are similar in strength to the in-band transitions. A possible idea to solve the problem would be to interchange these two sequences for spin values $I \geqslant 21$. However, the present way of connecting the bands leads to a much more smooth behaviour as a function of spin than would be the case if the two sequences were interchanged. We also note that there is a weak transition connecting the even spin sequences of these two bands, i.e. a transition from the $I = 16$ state of band 3 to the $I = 14$ state of band 4 (this connection was first identified after the theoretical analysis suggested that a strong interaction should exist between the two structures). Thus, a possible (and perhaps more logical) alternative would be to interchange the even spin sequences of these two bands for spin values $I \geqslant 14$.

The crossings between the even spin negative parity states are illustrated in Fig. 3(a). A closer look at the observed states in that figure does not only suggest the crossing between bands 3 and 4 around $I = 14$ but also a crossing between bands 3 and 5 around $I = 11$. In order to find out if this scenario appears consistent with the observed bands, we have carried out a three-band-mixing calculation. In this calculation, three smooth unperturbed bands, labelled as 3′, 4′ and 5′ are parameterised with a moment of inertia with a linear dependence on I. They interact with strengths which are assumed to be constant over the spin range considered, $I = 6$–20. With a least-square fit, all observed states in this spin range are reproduced within ± 5 keV with an interaction matrix