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LETTER TO THE EDITOR

First observation of a rotational band in neutron-rich ^{180}Lu

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Abstract
Rotational states assigned to a $K^\pi = (5^+)$ band in $^{180}_{71}$Lu$_{109}$ have been populated in the decay of a $t_{1/2} \geqslant 1$ ms, two-quasiparticle isomer. Delayed γ-ray and x-ray coincidences were observed with the Gammasphere array following the deep-inelastic reaction $^{238}_{92}$U + $^{180}_{72}$Hf. Gamma-ray coincidence and intensity data, comparisons with the level structure of the neighbouring odd–odd isotone, a g-factor analysis and theoretical predictions of multi-quasiparticle states, all support the assignment of the new band to the neutron-rich nucleus ^{180}Lu.

The rare-earth elements around $A \approx 180$ have proton and neutron orbitals lying close to the Fermi surface with large angular momentum projections, Ω, on the nuclear symmetry axis. When combined with the pronounced mid-shell prolate deformations in these nuclei, the total angular momentum projection, K $(= \sum_i \Omega_i$, for i unpaired particles) becomes an approximately conserved quantity. Metastable or isomeric states, corresponding to configurations with maximally aligned spins along the symmetry axis, arise because they decay by transitions that have to effect a large change in the K quantum number and are thus hindered. However, the study of these states has predominantly been restricted to the neutron-deficient side of the β-stability line. Although predictions exist [1] for long-lived high-K states in neutron-rich nuclei, these cannot be populated using fusion–evaporation reactions with stable beam and target combinations.

Lutetium isotopes ($Z = 71$) have some of the largest quadrupole deformations in the $A \approx 180$ region and some of the longest lived K-isomers observed so far. They also exhibit

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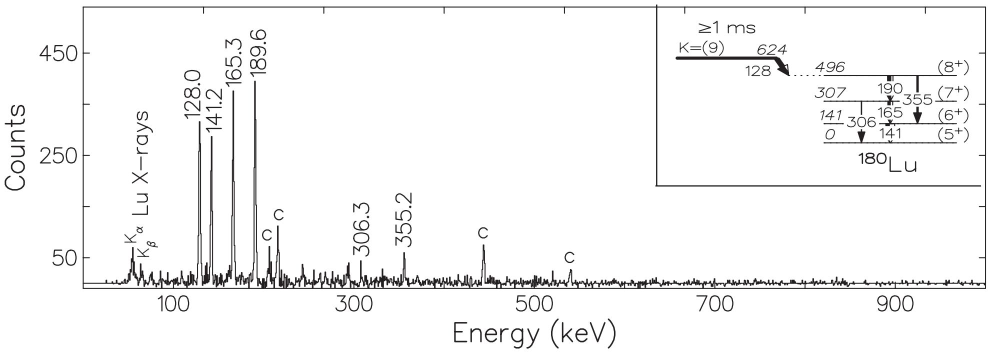

Figure 1. Gamma-ray spectrum produced from summing the coincidence spectra created by double-gating on transitions in the new band. Coincidences with lutetium x-rays can be clearly seen. Contaminants are labelled with 'c'. The proposed level scheme is shown in the inset. The energies of the levels are relative to the lowest state only. Tentative spins and parities are given in brackets (see text for details).

unusual phenomena including K-driven β-decays [2]. The longest-lived lutetium isomers are in the neutron-rich isotopes. For example, a 160 day three-quasiparticle isomer has been identified in ^{177}Lu [2]. Indeed, ^{177}Lu is the most neutron-rich isotope that can be populated in fusion–evaporation reactions and even with light-ion projectiles (^{7}Li and ^{4}He) the population takes place through the weak $\alpha 2n$ and $p2n$ channels. To study more neutron-rich isotopes, it is necessary to use another method. Historically, transfer reactions with tritium beams have been used to identify low-spin states in ^{178}Lu and ^{179}Lu [3]. However, this technique is generally restricted to in-beam spectroscopy of low-lying states. Several recent studies [4–8] using deep-inelastic reactions with heavy-ion projectiles have proved very successful in populating high-K isomers in neutron-rich nuclei. In this letter we report the first observation of an isomeric state in ^{180}Lu, lying five neutrons beyond the β-stability line. This isomer was discovered following a multi-nucleon transfer experiment using a pulsed uranium beam on the heaviest stable isotope of hafnium. New isomers in ^{180}Ta from this study are published in [8].

The ATLAS accelerator facility at Argonne National Laboratory delivered a 1.6 GeV, pulsed ^{238}U beam on a 40 mg cm^{-2} ^{180}Hf target, backed with $\geqslant 50$ mg cm^{-2} of $^{\mathrm{nat}}$Pb. The pulsed beam ($\tau_{\mathrm{pulsing}} = 82.5$ ns) at an energy 15% above the Coulomb barrier, was chopped on two time ranges with on/off conditions of 8.25/16.5 μs and 2/4 ms, respectively. The recoils were stopped at the target position at the focus of the Gammasphere array [9], comprised of 98 γ-ray and three x-ray Compton-suppressed Ge detectors. The master trigger required at least one Ge detector to fire in the beam-off period. The delayed events were analysed using γ–γ, γ–x-ray and γ-time coincidence matrices as well as a γ–γ–γ cube. Isomeric states up to (24) $\hbar$ have been observed [8] in the multi-nucleon transfer channels.

Several new transitions, in coincidence with lutetium x-rays, have been observed with energies of 128, 141, 165 and 190 keV (see figure 1). Gamma-ray coincidences have been used to order these decays into a rotational sequence and crossover transitions have been established for all but the 128 keV decay (see the inset of figure 1). This band does not correspond to any previously known structure in lutetium nuclei.

Due to the low energy of the 128 keV transition, the multipolarity can be found by balancing the 'missing' intensity with the electron conversion. Assuming that the 141, 165 and 190 keV transitions are magnetic dipole transitions, with E2 crossovers at 306 and 355 keV, yields a total electron conversion coefficient for the 128 keV decay of $\alpha_T(\text{expt}) = 0.3 \pm 0.1$, resulting in a firm E1 assignment ($\alpha_T(\text{E1}) = 0.19$, $\alpha_T(\text{E2}) = 1.3$, $\alpha_T(\text{M1}) = 1.9$).

Although there are insufficient statistics to obtain a decay curve for the new lutetium isomer in the 4 ms time range, a limit of $t_{1/2} \geqslant 1$ ms was obtained by comparing the relative intensity of the new isomer on both the 16.5 μs and 4 ms time ranges. The transitions assigned to the lutetium band were found to be enhanced in the long-time range by a factor of $\sim$2 compared with known millisecond isomers (e.g. the 0.8 ms isomer in ^{174}Yb [3]), suggesting that the new isomer is longer-lived.

The relative intensity of the new band is $\approx$1% of the population of the 8^- isomer in the ^{180}Hf target. This yield is consistent with the transfer of a few nucleons. For example, low-lying isomers in the tantalum isotopes ($Z = 73$) $A = 178$–182 have been observed with similar relative intensities. (Isomers in tantalum isotopes outside this mass range are considerably weaker.) In addition, the low energy of the transitions in the new band strongly suggests a one- or two-quasiparticle assignment. The one-quasiparticle systematics for the odd-A lutetium isotopes extend to ^{179}Lu and involve low-lying $K^\pi = \frac{7}{2}^+[404]$ and $\frac{9}{2}^-[514]$ bands. However, the transition energies in the lutetium band observed here are too low to form the $\frac{9}{2}^-$ band in ^{181}Lu and are higher than expected for the $\frac{7}{2}^+$ band in the same nucleus, although a $K^\pi = \frac{7}{2}^+$ assignment cannot be strictly ruled out from the energy systematics alone. (The quadrupole deformation is decreasing with increasing mass in this region, which is manifested as increasing transition energies.) Examining the in-band γ-ray branching ratio of the $\Delta I = 2/\Delta I = 1$ transitions ($= 0.11 \pm 0.04$ and 0.40 ± 0.05 for the 307 and 496 keV levels, respectively), assuming $K = \frac{7}{2}$, gives an average value for the two levels of $\frac{(g_K - g_R)}{Q_0} = 0.16 \pm 0.04$ (e·b)$^{-1}$, in poor agreement with the theoretical value [10] of 0.06 $(e \cdot b)^{-1}$. The known $K = \frac{7}{2}$ bands in lutetium nuclei have experimental g-factors in very close agreement with this theoretical value. Therefore, it does not seem possible to assign the newly observed band to one of the neutron-rich odd-A lutetium isotopes. Neither do the band transition energies match those known in even-A isotopes.

The first neutron-rich even-A lutetium isotope where there are no known rotational structures is $^{180}_{71}\text{Lu}_{109}$. The 5.7 m ground state has a (3^-) assignment, above which lie several excited (low-spin) states populated in the β^- decay of the 0^+ ^{180}Yb ground-state [11]. Examination of the neighbouring odd–odd isotone $^{182}_{73}\text{Ta}_{109}$ reveals a $K^\pi = 5^+$ bandhead at 16 keV ($t_{1/2} = 283$ ms) fed by a 15.8 m $K^\pi = 10^-$ isomer at 335 keV [3]. (The 114 day ground state has a $K^\pi = 3^-$ assignment.) The first two dipole transitions have energies of 147 and 172 keV, respectively, very close to those observed in the new lutetium band (with energies of 141 and 165 keV, respectively). Extracting the g-factors for the new band assuming $K^\pi = 5^+$, yields an average of $\frac{(g_K - g_R)}{Q_0} = 0.10 \pm 0.03$ $(e \cdot b)^{-1}$. This is in excellent agreement with the expected value of 0.10 $(e \cdot b)^{-1}$ for the $\pi\{\frac{9}{2}^-[514]\} \otimes \nu\{\frac{1}{2}^-[510]\}$ $K^\pi = 5^+$ configuration. (The in-band branching ratio for the $K^\pi = 5^+$ band in ^{182}Ta also gives $\frac{(g_K - g_R)}{Q_0} = 0.10 \pm 0.03$ $(e \cdot b)^{-1}$ [3].) Many other rotational bands have been observed in ^{182}Ta, but the $K^\pi = 5^+$ band is the only two-quasiparticle structure identified with transition energies similar to those of the new lutetium band, supporting the placement of the new band in ^{180}Lu and a $K^\pi = 5^+$ assignment. Adding one unit of spin for each level above the suggested $K^\pi = 5^+$ bandhead leads to a $K^\pi = 9^-$ assignment for the isomer (assuming that there are no unobserved low-energy transitions). It should be noted that while an alternative assignment to ^{182}Lu is also possible, this would involve the transfer of four nucleons to/from ^{180}Hf, as opposed to two nucleons for ^{180}Lu. Therefore, this is less likely due to the reduced population intensity that would be expected.

Blocked BCS calculations, including residual nucleon–nucleon interactions, of the type described by Jain *et al* [12], predict a $K^\pi = 3^-$ ground state, in agreement with [11], and a $K^\pi = 5^+$ configuration at about 26 keV for ^{180}Lu. The most favoured higher K two-quasiparticle states are calculated to lie at ≈700 keV, with configurations of $K^\pi = 8^+$: $\pi\{\frac{9}{2}^-[514]\} \otimes \nu\{\frac{7}{2}^-[503]\}$, $K^\pi = 9^-$: $\pi\{\frac{9}{2}^-[514]\} \otimes \nu\{\frac{9}{2}^+[624]\}$ and $K^\pi = 10^-$: $\pi\{\frac{9}{2}^-[514]\} \otimes \nu\{\frac{11}{2}^+[615]\}$. Unlike in ^{182}Ta, the $K^\pi = 9^-$ state is expected to lie below the $K^\pi = 10^-$ state in ^{180}Lu, due to the implied reversal in the single-particle energies at $^{181}_{72}\mathrm{Hf}_{109}$ [7] so that the $\frac{9}{2}^+[624]$ neutron orbital lies below the $\frac{11}{2}^+[615]$ level[7]. It is worth noting that in ^{178}Lu the $K^\pi = 9^-$ configuration lies at 120 keV with a half live of 23 m [3]. The $K^\pi = 8^+$ configuration has not been observed in either ^{182}Ta or ^{178}Lu.

The predicted energy of the $K^\pi = 8^+$, 9^- and 10^- states is close to that of the isomer feeding the new band observed in the current work, and in addition a $K^\pi = 9^-$ assignment would result in an E1 decay to the 8^+ rotational state in the suggested $K^\pi = 5^+$ band. Hence, a coherent picture appears to emerge.

Many unsuccessful attempts have been made to establish the presence of a high-K isomeric state in ^{180}Lu, see, for example [11, 13–15], because of its bearing on the astrophysical production of ^{180m}Ta [16]. However, these searches concentrated on the observation of half-lives > 10 s and β-decays to ^{180m}Hf. The data from these previous experiments therefore suggest an upper limit of $t_{1/2} \leqslant 10$ s for the new isomer. It is interesting to note that the calculations in the earlier studies also predict low-lying $K^\pi = 9^-$ and 8^+ configurations [11, 13, 14].

The observation of this millisecond high-K isomer opens up the possibility of using 'isomer tagging' to establish states above the isomer, enabling prompt γ-rays to be assigned from future deep-inelastic measurements and hence establish high-spin structures in the neutron-rich domain. Prompt spectroscopy could also extend the observed rotational band.

In summary, the experimental evidence from x-ray coincidences, transition energies, relative population intensity and g-factors obtained from in-band branching ratios support a two-quasiparticle $K^\pi = 5^+$ band assignment in ^{180}Lu. Multi-quasiparticle calculations predict three high-K states within ≈100 keV of the observed isomeric state and a $K^\pi = 9^-$ configuration reproduces the observed electric dipole isomeric decay.

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[7] In ^{181}Hf the $\frac{9}{2}^+[624]$ neutron state is isomeric [7], whereas the $\frac{11}{2}^+[615]$ single-quasiparticle state has not been observed and is therefore assumed to lie higher in energy. This is consistent with the trend of increasing energy for the $\frac{11}{2}^+[615]$ orbital as Z decreases for the $N = 109$ isotones. Over the same range of Z, the energy of the $\frac{9}{2}^+[624]$ state changes very little.

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