BRIEF REPORTS

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A $K^\pi = 8^-$ isomer in ^{136}Sm

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An isomer with a half-life of 15±1 μs has been observed in the N=74 nucleus ^{136}Sm, populated following the reaction ^{107}Ag(^{32}S,$p2n$)^{136}Sm. It is proposed to have a $K^\pi = 8^-$ two quasineutron configuration. The isomer decays via a ΔK=8, 466 keV $E1$ transition with a surprisingly low hindrance per degree of K forbiddenness, f_ν=25.

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Isomeric K^π=8$^-$ states from the coupling of the 7/2$^+$[404] and 9/2$^-$[514] proton orbitals have been observed in all the even-N hafnium (Z=72) isotopes from ^{170}Hf to ^{182}Hf as cataloged in Refs. [1,2]. Considerably less is known about the analogous neutron configuration, which, due to small differences between the neutron and proton potentials, should be most favored in N=74 nuclei. Candidates for such states with half-lives in the millisecond region have been observed in ^{130}Ba [3], ^{132}Ce [4], and ^{134}Nd [5]. This paper reports the results of the search for an equivalent state in ^{136}Sm$_{74}$. Since the $\frac{7}{2}^+$ and $\frac{9}{2}^-$ ground states of ^{135}Sm and ^{137}Sm can be associated with the 7/2$^+$[404] and 9/2$^-$[514] Nilsson orbitals, respectively, one would expect a K^π=8$^-$ two quasineutron state with an excitation energy close to twice the neutron pair gap. A recent publication [6], reported high-spin states in ^{136}Sm, but gave no information about decays from isomeric states.

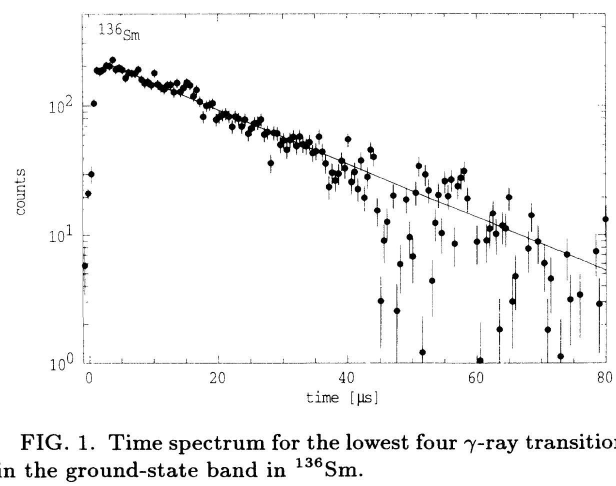

FIG. 1. Time spectrum for the lowest four γ-ray transitions in the ground-state band in ^{136}Sm.

In the present study, ^{136}Sm was populated using the reaction ^{107}Ag(^{32}S,$p2n$)^{136}Sm at a beam energy of 140 MeV. The pulsed beam, provided by the 14UD tandem accelerator at the Australian National University, was incident on a 4 mg/cm^2 thick enriched (99%) ^{107}Ag target. Emitted γ rays were detected using the six-detector Compton-suppressed array, CAESAR [7] with pairs of detectors placed at angles of ±48°, ±147°, and ±97° to the beam direction. A seventh, planar detector was placed at 45° to increase the detection efficiency for low-energy

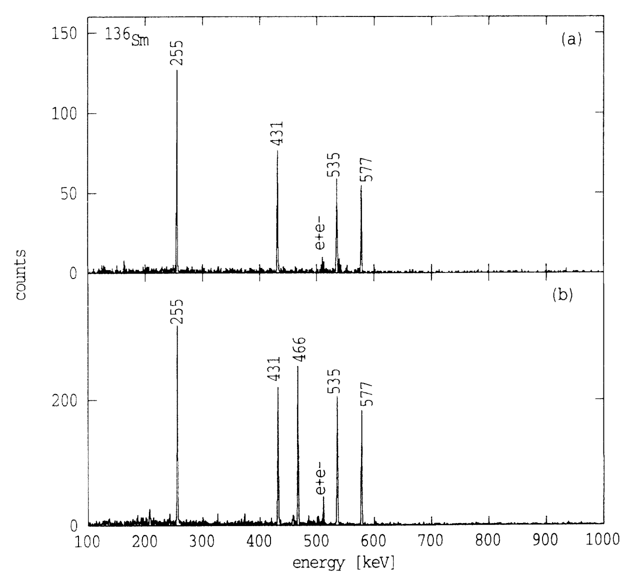

FIG. 2. (a) γ-ray spectrum showing transitions in coincidence with the 466 keV transition in the out-of-beam γ-γ matrix. (b) Summed γ-ray spectrum showing transitions in coincidence with the first four transitions in the ground-state band in the out-of-beam γ-γ matrix.

γ rays. γ-ray-time experiments were performed in which the seven detectors shared a common time-to-amplitude converter (TAC), started with an RF pulse train in phase with the beam pulse and stopped with a γ-ray signal. The TAC range used was 1 ms, with the beam on for 10.7 μs and off for 856 μs. Matrices of time against γ-ray energy were then constructed off-line. Background subtracted time projections with energy gates set on the lowest four ground-state band transitions were found to have a delayed component. The combined time spectrum, shown in Fig. 1, implies the existence of an isomer with a half-life of 15$\pm$1 μs.

In order to deduce the coincidence relationships between γ rays associated with isomers, a $\gamma-\gamma$-time coincidence experiment was performed in which each germanium detector energy signal was accompanied by its corresponding time with respect to the pulsed beam. The beam was chopped and bunched to arrive in 1 ns bursts, separated by 1.7 μs. By examining the time differences between γ-ray events, it could be deduced whether pairs of γ-rays were in prompt or delayed coincidence (through isomers). Additional constraints could be added to select individual γ-rays in the "in-beam" or "out-of-beam" periods. The criterion used to define a prompt coincidence was that the two γ-rays were observed within a time window of $\pm$17 ns. In order to search for coincidences across isomeric states, a γ-γ matrix was constructed of events which had a time difference of between 80 and 750 ns. In this case the first γ-ray observed is labeled *early* and the second one *delayed.* An additional condition requiring the *early* γ-rays to be in-beam could also be imposed.

In the out-of-beam, prompt γ-γ matrix, gates set on the ground-state band transitions showed a 465.9 keV transition which was also observed as a delayed line in the γ-time measurement discussed above. This transition is coincident with the transitions depopulating the 2^+, 4^+, 6^+, and 8^+ levels of the yrast band but not the 615 keV transition depopulating the yrast 10^+ level, as illustrated by the spectra in Figs. 2(a) and 2(b). The 466 keV gamma-ray depopulates a new isomeric state at an excitation energy of 2264.5 keV, as shown in Fig. 3. The absence of branches to the 6^+ yrast level argues against

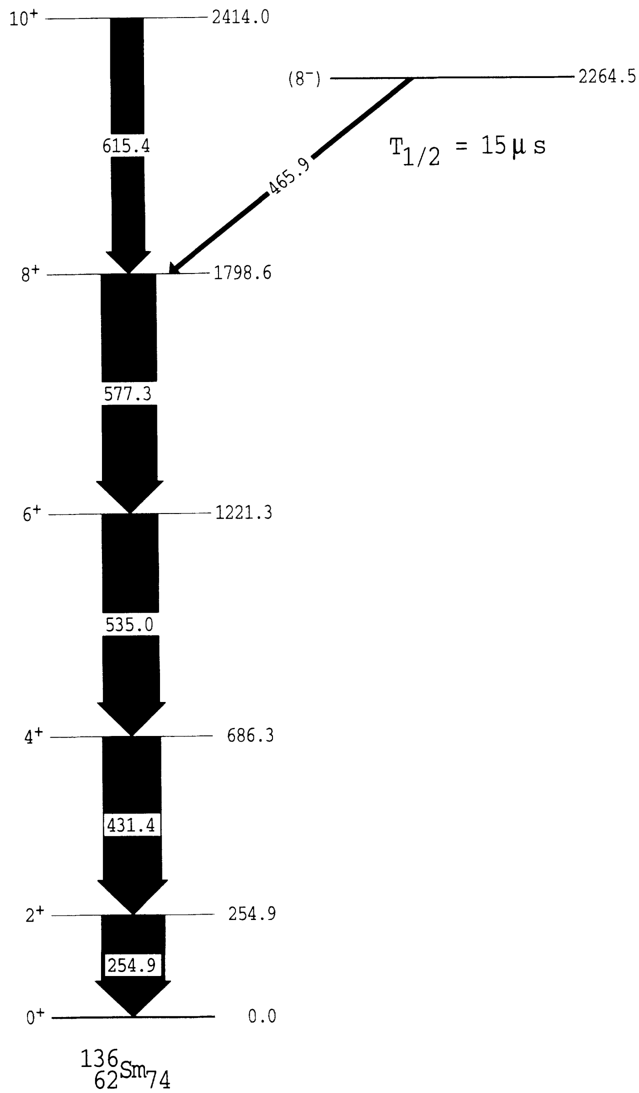

FIG. 3. Partial level scheme for ^{136}Sm showing the new isomeric state at 2264.5 keV.

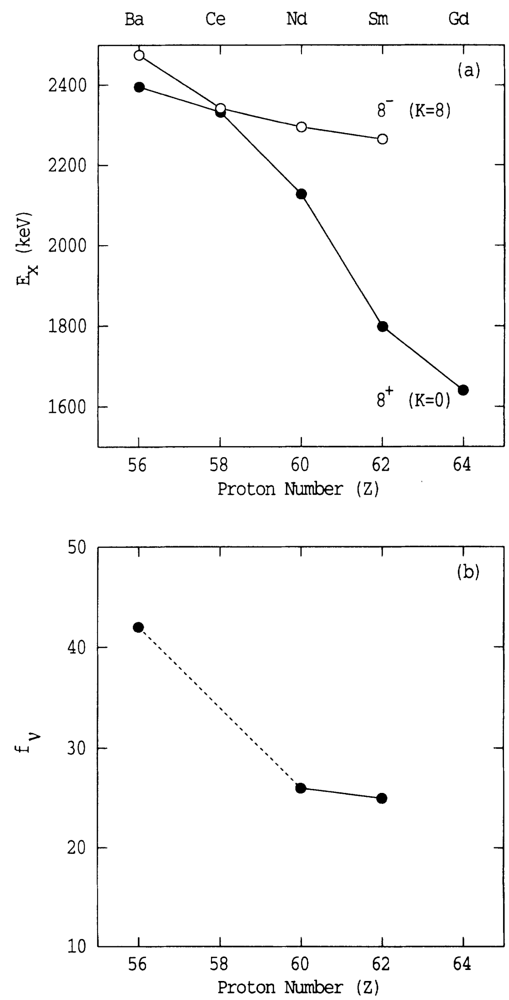

FIG. 4. (a) Comparison of $K^{\pi}=8^-$ level energies with the yrast $I^{\pi}=8^+$ energies for the $N=74$ isotones. (b) Comparison of measured f_ν values for observed $E1$ decays out of the $K^{\pi}=8^-$ isomers in the $N=74$ isotones. The statistical uncertainties are smaller than the data points.

TABLE I. Summary of $E1$ decays of $K^{\pi}=8^{-}$ isomers in $N=74$ isotones.

Nucleus	$E_x(8^-)$ (keV)	$2\Delta_{oe}$ (keV)	E_γ $(8^- \to 8^+)$ keV	$T_{\frac{1}{2}}$	f_ν
^{130}Ba	2475.1	2663	80.3	8.8±0.2 ms	42
^{132}Ce	2340.8	2645	(10)	13±2 ms	—[a]
^{134}Nd	2294.0	2675	166.5	410±30 μs	26
^{136}Sm	2264.5	2445	465.9	15±1 μs	25

[a]The associated 10 keV $E1$ decay to the 8^+ level has not been observed.

an 8^+, or lower, spin assignment but the weak population of the isomer (~7% of the total ^{136}Sm intensity) is consistent with a spin/parity assignment of 8^-. If the level had $I^{\pi}=9^{\pm}$ or $10^{\pm}$ it would be yrast and therefore probably more strongly populated.

States above the new isomer are important as they would provide an independent test of the proposed structure. In order to attempt to identify transitions above the new isomer, gates were set on the first four ground-state band transitions on the delayed axis of the delayed-prompt matrix. The resulting "earlies" spectrum showed evidence for a 414 keV γ ray directly feeding into the isomer. However, the intensity above this transition appears to be fragmented, and no clear band structure was evident. The small number of counts and the associated difficulty in identifying additional transitions above the isomer arises from its long half-life (15 μs) relative to the timing limits for the $\gamma-\gamma$-time measurements (< 750 ns). Nevertheless, we can associate the observed isomeric state with the expected $K^{\pi}=8^{-}$, two quasineutron configuration. Using the extrapolated masses for the ^{134,135,136,137}Sm isotopes from Ref. [8] the third-difference neutron pair gap is 1.22 MeV. Therefore, the two quasineutron $K^{\pi}=8^{-}$ state should lie at approximately 2.4 MeV, within 0.2 MeV of the experimentally observed isomer. Note that $K=8$ is the maximum that can be made by combining two orbitals near the Fermi surface.

A comparison of the excitation energy of the new isomer, with analogous states in other $N=74$ isotones is shown in the top portion of Fig. 4. The energy in ^{136}Sm is the lowest yet observed in an $N=74$ nucleus, although the downward trend is not as marked as that of the ground-state band $K=0$, $I^{\pi}=8^{+}$ state, a trend which is indicative of the increasing collectivity in the ground-state band with increasing proton number. The decay properties [9] can be compared through the *hindrance per degree of K-forbiddenness*, $f_\nu = [T^{\gamma}_{1/2}/T^{W}_{1/2}]^{1/\nu}$, where $T^{\gamma}_{1/2}$ is the partial γ-ray half-life, $T^{W}_{1/2}$ is the Weisskopf single-particle estimate, the degree of forbiddenness $\nu = \Delta K - \lambda$ and λ is the transition multipolarity. For a $\Delta K=8$, 466 keV $E1$ transition and a half-life of 15±1 μs, the calculated f_ν value is 25. Table I compares the values for the $K^{\pi}=8^{-}$ isomers in the $N=74$ isotones and the data are also illustrated in Fig. 4(b). It is evident that the ^{136}Sm case continues the fall in f_ν with increasing Z and indeed has the lowest value observed for a $\Delta K=8$ $E1$ transition. This is despite the increased collectivity noted above which would suggest that K should be a good quantum number and therefore that the $K^{\pi}=8^{-}$ isomer in ^{136}Sm should have a larger f_ν value than those of analogous transitions in the lighter $N=74$ neighbors. Similar anomalous behavior is observed in the $N=106$ isotones [2] where there is an increase in the hindrance factors as the $Z=82$ shell gap approaches and the nuclei become more gamma soft. The empirical evidence therefore points to some other degree of freedom at work and one such possibility could be that the hindrance factors are influenced by shape isomerism as well as K isomerism.

In summary, we have observed in ^{136}Sm a new isomeric state at 2.265 MeV. Its decay properties and its excitation energy are compared with the $K^{\pi}=8^{-}$ isomers in other $N=74$ isotones. The measured half-life of 15±1 μs corresponds to a hindrance per degree of K forbiddenness for this decay of 25, the lowest value yet observed for a $\Delta K=8$, electric dipole decay.

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