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Recent Experiments at Brookhaven:

Level Structure of $N = 86$ Isotones ^{156}Yb and ^{150}Gd

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Abstract

Recent experiments at Brookhaven: level structure of $N = 86$ isotones ^{156}Yb and ^{150}Gd . A. W. Sunyar (Department of Physics, Brookhaven National Laboratory, Upton, New York 11973 U. S. A.).
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States of the $N = 86$ isotones ^{156}Yb and ^{150}Gd have been studied by means of the $^{144}\text{Sm}(^{16}\text{O}, 4n)^{156}\text{Yb}$, $^{113}\text{In}(^{46}\text{Ti}, p2n)^{156}\text{Yb}$ and the $^{124}\text{Sn}(^{30}\text{Si}, 4n)^{150}\text{Gd}$ reactions. Levels have been established to spin $36 \hbar$ and over 12.5 MeV in excitation in ^{150}Gd and to beyond spin $25 \hbar$ in ^{156}Yb . The systematics of levels in the $N = 86$ isotones from ^{150}Gd to ^{156}Yb are described, and the near-spherical shell model description for states in this region to near spin $30 \hbar$ is discussed. A $T_{1/2} = 6$ nsec, 72-keV isomeric transition in ^{156}Yb has been discovered, and an E1 multipolarity is assigned to this transition. The spin-parity of the isomeric state is established as 11^- .

Recent Experiments at Brookhaven:

Level Structure of $N = 86$ Isotones ^{156}Yb and ^{150}Gd

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Early studies of the $N = 86$ nuclei ^{152}Dy [1] and ^{154}Er [2] resulted in identification of discrete states at very high spin, in the neighborhood of $38\hbar$, at excitation energies which exceeded 12.5 MeV. Isomers were also observed[3] in this region, and lifetime measurements by Doppler shift techniques of several high spin states have been reported.[4] A great deal of experimental and theoretical effort has been expended in efforts to clarify the structure of these and other nuclei just above the magic $N = 82$ shell closure and the $Z = 64$ semi-magic subshell closure. Many structural features of these nuclei appear to arise from relatively simple single particle configurations in a near-spherical potential. The available shell model orbitals which play a major role in this region are illustrated in Fig. 1. In an effort to extend the available experimental information in this region with a view towards identification of systematic trends across the $N = 86$ isotones, studies of ^{150}Gd and ^{156}Yb have been initiated at the Brookhaven MP Tandem Facility. Preliminary results of this work will be presented here.

^{156}Yb has been investigated by means of the reactions $^{144}\text{Sm}(^{16}\text{O}, 4n)^{156}\text{Yb}$ ($E = 70\text{--}120$ MeV) and $^{113}\text{In}(^{46}\text{Ti}, p2n)^{156}\text{Yb}$ ($E = 190\text{--}210$ MeV). The abundance of competing reactions necessitated the use of particle-gamma, K x-ray-gamma, as well as gamma-gamma coincidence experiments for identification of the transitions associated with ^{156}Yb . In addition,

gamma-ray excitation functions, linear polarizations and angular distributions were measured in the course of these experiments. The resulting decay scheme is shown in Fig. 2, where assignments of spin and parity are considered firm up to the $J, \pi = 17^-$ state. From the 17^- to the 25^- state, some re-ordering may be necessary in the future because of difficulties associated with similar transition intensities.

Several interesting features emerge from an examination of the ^{156}Yb level scheme of Fig. 2.

(1) A marked similarity to the low-lying level sequence in ^{154}Er (see Fig. 2 of Ref. 2) is immediately apparent.

(2) An isomeric state exists in both nuclei at about the same spin and excitation energy.

(3) The population of the positive parity band (observed to only the probable 12^+ state in ^{156}Yb) is considerably weaker ($< \sim 5\%$ of the main cascade) than in ^{154}Er , where the corresponding positive parity band is now known to spin 20.

(4) The 7^- and 9^- states observed in the decay of the 40 nsec isomer of ^{154}Er are not seen in the decay of the 6 nsec ^{156}Yb isomer.

(5) In contrast to the case of ^{154}Er , the isomeric transition in ^{156}Yb has been directly observed. This circumstance permits measurements (described below) which provide the basis for a rigorous spin and parity assignment of 11^- to the ^{156}Yb isomeric state and, by inference, to the ^{154}Er isomer as well.

(6) The energy spacing of the level sequence from the 11^- to 17^- states suggests a typical $(f_{7/2})^2$ neutron configuration built on

top of the 11^- isomer. This presumably terminates in the aligned neutron configuration $\left[(f_{7/2})^2_6 \times (h_{9/2}, i_{13/2})_{11^-} \right]_{17^-}$. Above this configuration one may expect levels which can be described in terms of both proton and neutron excitations.

The series of measurements which determine the energy, half-life and multipolarity of the ^{156}Yb isomeric transition include:

- (1) γ - γ coincidence measurements of low-energy electromagnetic radiation gated by clean high energy lines of ^{156}Yb to measure the energy and intensity of the isomeric transition.
- (2) Time correlation measurements of γ -radiation relative to the pulsed beam.
- (3) Gamma-ray angular distribution measurements relative to beam direction.

An example of a time correlation spectrum of γ -rays relative to beam pulse is shown in Fig. 3. A half-life of 6.0 ± 0.5 nsec for the isomeric state is derived from these data. The low-energy photon coincidence measurements show the presence of an intense 72-keV transition whose unconverted intensity fits well with that expected for an E1 transition ($\alpha_1 \approx 0.94$) rather than with that expected for an M1 transition ($\beta_1 \approx 10.7$). In addition, the $W(\theta)$ measurement for the 72-keV transition is consistent with that for a $\Delta J = -1$ transition feeding the known 10^+ state with a mixing ratio $\delta \approx -0.1$. We thus conclude that the 6.0 nsec isomeric state has 11^- spin and parity and decays with a 72-keV predominantly E1 transition to the 10^+ state. A probable dominant configuration for the 11^- state is the $\nu [h_{9/2}, i_{13/2}]_{11^-}$ aligned configuration.

A detailed comparison of ^{156}Yb and ^{154}Er levels which emphasizes the nearly identical nature of the spectra below the states with $J, \pi = 21^-$ is shown in Fig. 4. It may be remarked that 21^- is the maximum aligned spin-parity available from 4 neutrons beyond $N = 82$ in the shell-model space shown in Fig. 1.

The effective moments of inertia for these two $N = 86$ nuclei are quite similar above spin 15 with $\mathcal{J} \doteq 141 \text{ MeV}^{-1}$ for ^{156}Yb and 142 MeV^{-1} for ^{154}Er , a value some 13% in excess of the rigid sphere value.

Although we have emphasized similarities in the high spin level structure of these nuclei (at least to spin of the order of 21), the prospect for extending the comparison to very high spins is unfortunately limited. This results from a definite decrease in the population of high spin states above $J = 25$ in ^{156}Yb . While ^{154}Er states are strongly populated at high spin (60% of the ground state intensity at $J = 25$), the corresponding number for ^{156}Yb is only about 25%. As remarked earlier, a similar reduction in feeding of the positive parity band also occurs.

The $N = 86$ nucleus ^{150}Gd was studied by means of the $^{124}\text{Sn}(^{30}\text{Si}, 4n)^{150}\text{Gd}$ reaction at 140 MeV. Experimental spectroscopic techniques similar to those mentioned earlier were used to establish the disintegration scheme. Fig. 5 shows the yrast states to spin 36 $\hbar$ and over 12.5 MeV in excitation energy deduced from our measurements. Previous work by Haenni et al. [5] had established the lower part of this scheme (below the 10^+ and 17^- states) by means of the $(\alpha, 4n)$ reaction, and our results agree with their work. Other features of the scheme include:

(1) In contrast to ^{152}Dy , ^{154}Er and ^{156}Yb , no isomeric state with $T_{1/2} \geq 5$ nsec has been observed.

(2) Low-lying states ($J \leq 18$) exhibit a strong similarity to those in the other $N = 86$ even-even nuclei.

(3) The effective moment of inertia, obtained from the slope of the yrast energy vs. $I(I+1)$ plot above the $I = 16^+$ state, is $\mathcal{J}_{\text{eff}} \approx 140 \text{ MeV}^{-1}$, very close to the ^{152}Dy , ^{154}Er and ^{156}Yb values.

The systematics of the yrast energy-levels of $N = 86$ isotones from ^{150}Gd to ^{156}Yb are shown in Fig. 6. A number of trends are apparent in these data up to spin 17.

(1) The excitation energies of the $2+$ to $8+$ states decrease as Z increases.

(2) Low-lying negative parity states (3^- to 9^-) rise in excitation energy from $Z = 64$ to $Z = 68$ and are not observed in ^{156}Yb .

(3) A $10+$ state occurs in close proximity to an 11^- state. These states are fed by cascades which extend to $16+$ and 17^- , respectively, except for ^{156}Yb , where the positive parity cascade is not yet observed beyond 12^+ .

An extension of the extreme single particle approach of Kleinheinz et al. [6] permits one to describe these features as due mainly to the neutron $(f_{7/2})^2$ or $(f_{7/2}, h_{9/2})$ configurations coupled to the ground, the 3^- octupole phonon and to either the $(i_{13/2})^2_{10+}$ or the $(i_{13/2}, h_{9/2})_{11^-}$ configurations. As mentioned earlier, states with spins exceeding about $20 \hbar$ cannot arise from the maximal alignment of the 4 available valence neutrons and require contributions from the excitation of protons. It

is interesting to note the existence of a band-like sequence of states starting with 21^- in ^{150}Gd and ^{152}Dy and 19^- in ^{154}Er . These sequences of decreasing energy quadrupole transitions closely resemble the $0,2,4,6+$ energy spacings in the corresponding $(N-2)$ isotopes (see Fig. 6). Such a correlation suggests an interpretation involving a stretched configuration of

$$\left[(\pi h_{11/2})^2_{10^+(8^+)} \times (h_{9/2, i_{13/2}})_{11^-} \right]_{21^-, (19^-)} \quad \text{as}$$

bandheads to which one couples the $0,2,4,6+$ configurations to which the $(\nu f_{7/2})^2$ configuration is a major contributor. The recognizable features of such (j^2) configurations suggest that, in this region, relatively pure, near-spherical shell model states persist as a dominant excitation mode to high spins which approach $30 \hbar$.

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Figure Captions

- Fig. 1. Shell-model valence orbitals for neutrons and protons above $N = 82$ and $Z = 64$, respectively.
- Fig. 2. Level scheme for ^{156}Yb . Spin-parity assignments are firm to the 17^- state and tentative as to ordering above this spin.
- Fig. 3. TAC spectrum of γ -ray events in a Ge-Li detector in coincidence with the pulsed beam.
- Fig. 4. Low-lying level structure comparison of the $N = 86$ nuclei ^{154}Er and ^{156}Yb . Δ denotes the small unmeasured energy of the 11^- to 9^- ^{154}Er isomeric transition.
- Fig. 5. Level scheme for ^{150}Gd .
- Fig. 6. Systematics of yrast energy levels of $N = 86$ isotones ^{150}Gd , ^{152}Dy , ^{154}Er and ^{156}Yb . The dots adjacent to the 21^- to 27^- states in ^{150}Gd , ^{152}Dy and to the 19^- to 25^- states in ^{154}Er indicate the $0+$ to $6+$ level energies in the $(N-2)$ isotopes relative to the 21^- (19^-) states as bandheads.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6