Proton Single-Particle States above $Z = 64$

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From a (^{6}Li, $3n$) in-beam study of the one-particle nucleus ^{147}Tb the 1.6-h isomer is assigned at $\frac{1}{2}^+$ which is attributed to the $\pi s_{1/2}$ shell-model state. The $\pi d_{3/2}$ level lies at 253 keV, and the $\pi d_{5/2}^{-1} j_0^2$ and $\pi g_{7/2}^{-1} j_0^2$ states are found at 354 and 719 keV, respectively. These observations provide a clear and consistent picture of the single-proton states in this region. The discontinuity of the observed quasiparticle energies between $^{145}_{63}$Eu$_{82}$ and $^{147}_{65}$Tb$_{82}$ provides support for a large single-particle energy gap at $Z = 64$, estimated to be ~ 2.3 MeV.

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The ^{147}Tb nucleus has one proton outside the ^{146}Gd closed core and thus is the principal source of information on the single-particle energies of the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ shell-model states which occur above $Z = 64$. Two β-decaying isomers are known[1,2] in ^{147}Tb, and recently the high-spin excitations built on the 1.9-min $\pi h_{11/2}$ single-particle state were investigated[3] in an $(\alpha, 8n)$ experiment. There are, however, no data on the $s_{1/2}$ and $d_{3/2}$ single-proton states, and their energies could only be estimated by extrapolation[4,5] from the lower-Z $N = 82$ isotones.

Before our work the 1.6-h ^{147}Tb spin and parity had been assigned[1] as $\frac{5}{2}^+$ and had been attributed to the $d_{5/2}$ shell-model orbit. This assignment arose[2] from the systematic comparison of the ground-state spins of ^{145}Eu and of the $N = 84$ and 86 Tb isotopes which were adopted as $\frac{5}{2}^+$ from early α-decay data. In the meantime, however, the ^{151}Tb$_{86}$ ground-state spin has been measured in an atomic beam experiment[6] as $\frac{1}{2}$, and a detailed β-decay[7] study of 4.2-h ^{149}Tb$_{84}$ concludes that the ground state must also have $I^\pi = \frac{1}{2}^+$.

These findings diminish the basis for the $\frac{5}{2}^+$ assignment for ^{147}Tb. Moreover, the $\pi h_{11/2}$ nature of 1.9-min ^{147}Tb also makes a $d_{5/2}$ assignment for the 1.6-h level highly questionable. The $\pi h_{11/2} \to d_{5/2}$ $E3$ transition[8] in ^{145}Eu has 4 Weisskopf units (W.u.), and comparable $E3$ enhancements have been measured in several odd-proton nuclei[1,8] in this region. On the other hand a decay branch connecting the two ^{147}Tb isomers has not been observed, and therefore its partial half-life must be $\gg 1.9$ min. Since an $E3$ transition of 1 W.u. in ^{147}Tb has $T_{1/2} < 20$ sec (if $E_\gamma > 3$ keV),[1,9] a $d_{5/2}$ assignment for 1.6-h Tb appears very unlikely.

In ^{147}Tb one expects the $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$ single-proton states at low excitation. Since pairing is important at $Z = 64$, the $\pi d_{5/2}^{-1} j_0^2$ and $\pi g_{7/2}^{-1} j_0^2$ two-particle, one-hole levels are also expected at low energy, analogous to ^{145}Eu where, e.g., the $\pi h_{11/2} j_0^{-2}$ one-particle, two-hole state lies[1] at 716 keV. Other states in ^{147}Tb will involve excitation of the ^{146}Gd 3^- or 2^+ core states[5] at 1.6 and 2.0 MeV. The data on the other three single-nucleon nuclei, ^{145}Gd (Ref. 10), ^{145}Eu (Refs. 1 and 11), and ^{147}Gd (Refs. 1, 2, and 5), suggest that such states only occur above 1 MeV. [The lowest-lying known core-excited state is the $(\nu f_{7/2} \times 3^-)$ $\frac{13}{2}^+$ level[5,12] in ^{147}Gd which, because of strong interaction with the $\nu i_{13/2}$ single-particle state, comes as low as 997 keV.] One, therefore, would expect that in ^{147}Tb such core-excited levels would also occur above 1-MeV excitation.

The importance of pairing at $Z = 64$ has been demonstrated in a recent analysis of proton excitations in the $N = 82$ isotones by Chasman,[13] who directs particular attention to the level scheme of ^{147}Tb. This analysis suggests that the five single-particle levels of the $50 < Z \leq 82$ shell should lie well below 1 MeV in that nucleus.

In order to elucidate the interesting problems of ^{147}Tb and also to remedy the unsolved discrep-

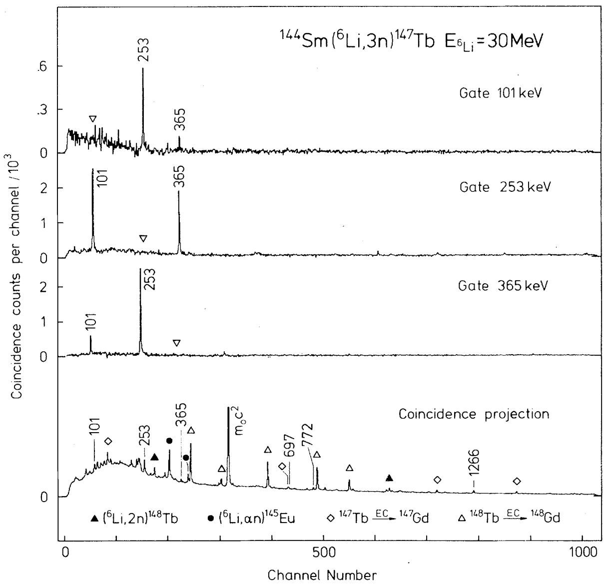

FIG. 1. Examples of coincidence spectra for transitions in ^{147}Tb measured in the (^{6}Li, $3n$) reaction with two 80-cm^3 coaxial Ge(Li) detectors.

ancies, we have investigated this nucleus through the ^{144}Sm(^{6}Li, $3n$) reaction at the FN tandem accelerator of Cologne University using in-beam γ and electron spectroscopy. A coincidence measurement at 30-MeV bombarding energy (Fig. 1) reveals a cascade of three γ rays with 101, 253, and 365 keV which, from excitation-function studies and coincidences with x rays, is attributed to ^{147}Tb. We have also observed this cascade in β decay of ^{147}Dy which was produced through the (α, $9n$) reaction with 120- to 140-MeV α-particle beams from our cyclotron. A β-decay study of mass-separated ^{147}Dy produced through (^{12}C, $7n$) reported in a recent abstract[14] independently establishes this result. Gamma rays of 101 and 253 keV also occur[1] in ^{149}Tb, but this nucleus is not observably populated in our ^{6}Li-induced in-beam measurements.

The properties of these three transitions are summarized in Table I. Conversion-electron measurements with a mini-orange spectrometer establish $M1$ multipolarity for the 253- and 365-keV transitions, and a γ-ray singles timing measurement with a pulsed beam gave $T_{1/2} < 1.3$ ns for the 253- and 365-keV γ rays, and < 2 ns for the 101-keV line.

The measured transition intensities, together with the intensities observed in the coincidence experiment (Fig. 1), establish the transition sequence as shown in the level scheme of Fig. 2. The intensity balance and the $T_{1/2}$ limit require magnetic dipole character for the 101-keV γ ray. The observed cascade, therefore, establishes four levels of the same parity.

Since, as discussed above, one expects only the $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$ states of the same parity below 1 MeV in ^{147}Tb, the dipole character of the cascade transitions requires that they form a monotonic spin sequence. The measured angular distributions exclude $I = \frac{1}{2}$ for the first and second excited states and thus are in accord with this conclusion. Since a $\frac{7}{2}^+$ lowest level would connect with the $\frac{11}{2}^-$ isomer through an $M2$ transition of $T_{1/2} < 10$ ms, the only possible spin sequence is $\frac{1}{2}$ (g.s.), $\frac{3}{2}$ (253 keV), $\frac{5}{2}$ (354 keV), and $\frac{7}{2}$ (719 keV) as shown in Fig. 2. [Here we have assumed that the energy separation between the two isomers is not $\ll 2$ keV, such that $\alpha_{tot}(M2)$ might become small.] The new $\frac{1}{2}^+$ assignment for the 1.6-h isomer removes the severe difficulties encountered with the previous $\frac{5}{2}^+$ assignment. The results also confirm that the $d_{3/2}$ level lies above the $s_{1/2}$ state, as suggested by extrapolation from the lower-Z $N = 82$ isotones.[4]

The position of the $h_{11/2}$ state relative to the positive-parity levels is not yet known, but its 1.9-min half-life excludes the possibility that it lies above the 354-keV $\frac{5}{2}^+$ state. A rather low excitation energy is suggested independently by an examination of the energy systematics of the odd

TABLE I. Properties of transitions in ^{147}Tb observed in the reaction ^{144}Sm(^{6}Li, $3n$) at 30-MeV bombarding energy.

E_γ (keV)	Relative γ-ray intensity	Angular-distribution coefficient A_2	A_4	$10^2 \alpha_K$	Multipolarity[a]
100.7(3)	23(3)	−0.09(2)	−0.02(2)	230(180)[b]	$M1$
253.4(2)	100	−0.15(1)	0.01(1)	14(2)	$M1$
365.1(3)	33(4)	−0.03(2)	0.01(2)	4.2(8)	$M1$

[a] Angular-distribution data given $E2$ admixtures < 5% for all three transitions.
[b] Value listed is α_{tot} derived from intensity balance.

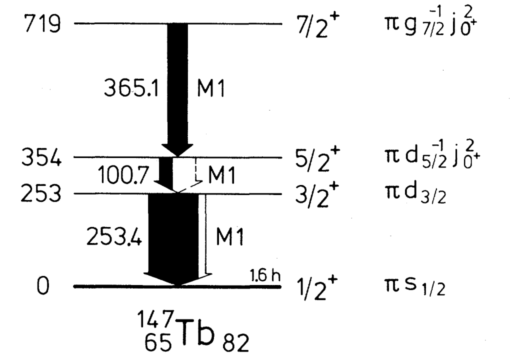

FIG. 2. Level scheme of ^{147}Tb established from the present experiments.

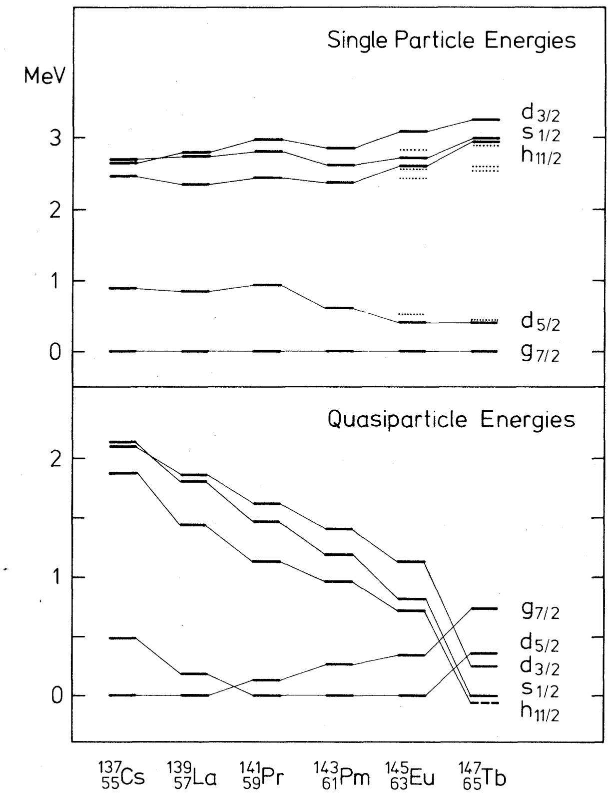

FIG. 3. Single-particle energies and quasiparticle energies calculated with $G = 0.20$ MeV for odd-Z $N = 82$ isotones. The calculated quasiparticle energies reproduce the experimental data within 20 keV. Chasman obtained-single particle energy gaps of 2.1 MeV for ^{147}Tb (Ref. 16) and 1.9 MeV for ^{145}Eu (Ref. 13) (dotted lines) with a pairing calculation based on the method of correlated quasiparticles using $G = 0.17$ MeV. If a pairing plus quadrupole interaction is included the Eu-gap value (Ref. 17) becomes 2.05 MeV.

Tb isotopes. In $^{151}Tb_{86}$ the $h_{11/2}$ level is found[15] at 100 keV, and for $^{149}Tb_{84}$ the α-decay data[1] suggest ~40-keV excitation for the $h_{11/2}$ state. From a pairing analysis of the measured level energies discussed below, one would expect that the $h_{11/2}$ level also lies very close to the $s_{1/2}$ state in ^{147}Tb.

Figure 3 illustrates the results of the pairing calculations for odd-Z $N = 82$ isotones carried out with a standard BCS program. In these admittedly simple, but straightforward, calculations $G = 0.20$ MeV was kept constant, and the single-particle energies were varied to reproduce the experimental quasiparticle energies. The final calculations for each nucleus were made without varying the single-particle energies, blocking each of the five individual single-particle states separately. The quasiparticle energies shown in the lower part of the figure, calculated in this manner from the single-particle levels shown above, agree within 20 keV with the experimental values from the present work and from Ref. 4. In the calculations for ^{147}Tb the four positive-parity states were reproduced, with the relative $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$ single-particle energies similar to those for ^{145}Eu. The calculated occupation probabilities for ^{144}Sm and the lighter even nuclei agree to within half a particle with experiment.[4] The calculations suggest about 2.3 MeV for the single-particle energy gap at $Z = 64$. This gap value is somewhat dependent on the details of the pairing calculation (cf. the caption to Fig. 3) but is in good agreement with our earlier approximate estimate[5] and is, as expected, slightly larger than the 1.829-MeV $d_{5/2}$ to $h_{11/2}$ energy separation observed[18] in ^{133}Sb.

In conclusion, the present study has located the four positive-parity single-proton states in ^{147}Tb, with the $s_{1/2}$ and $d_{3/2}$ states, and also the $h_{11/2}$ level, lying at low energy. This sequence is reversed as compared to the $Z = 63$ nucleus $^{145}Eu_{82}$, where the $d_{5/2}$ and $g_{7/2}$ states occur below the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ excitations. This pronounced discontinuity in the observed quasiparticle energies provides strong support for a large energy gap in the single-particle spectrum at $Z = 64$.

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Laser Enhancement of Nuclear β Decay

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Nuclear $\beta^{\mp}$ decay in the presence of a very intense laser field is considered. If the energy which is available for the decay in the absence of the field is small, the impact of the laser field is very significant, resulting in a large enhancement of the decay and a large upshift of the $\beta^{\mp}$ energies.

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Applications of lasers to nuclear physics have thus far been restricted to measurements of hyperfine or isotope shifts of atomic levels which provide information about nuclear quantities.[1] Directly influencing nuclear phenomena by a laser field seems hopeless at first glance. However, laser fields (albeit well focused) are of practically infinite extent compared to nuclear dimensions. Hence, although nuclear matrix elements are hardly affected by the laser, the quantum states of charged particles which evolve from nuclear processes are. For example, the state of a free electron in the presence of a laser field is given by the Volkov solution [Eqs. (2) and (3)].

The basic dimensionless parameter which turns out to govern all these effects is (we use units such that $\hbar = c = 1$)

$$\nu^2 = (ea/M)^2 = 7.5\times10^{-11}\lambda^2[\mathrm{cm}]I[\mathrm{W/cm^2}](m/M)^2, \qquad (1)$$

with a, λ, and I the field strength of the vector potential, the wavelength, and the intensity of the laser field; M is the mass of the charged particle

