PHYSICAL REVIEW C VOLUME 36, NUMBER 5 NOVEMBER 1987

Magnetic properties of the ^{176}Lu ground-state band

M. Déléze, A. Bruder, S. Drissi, and J. Kern
Physics Department, University of Fribourg, CH-1700 Fribourg, Switzerland

G. L. Struble
University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 30 April 1987)

The lowest members of the ^{176}Lu ground-state band have been Coulomb excited by ^{16}O ions. From the observed branching ratios and angular distribution coefficients, we obtain $G^{KK}/Q_0=0.18(1)$. Combining this result with the known magnetic moment of the ground state, we derive $g_R=0.288(9)$ and $(g_{\Omega_p}+g_{\Omega_n})=0.953(3)$. These values are in substantial agreement with semiempirical model predictions.

I. INTRODUCTION

In the decade ~1965–1975 a large number of deformed odd-odd nuclei close to and on the neutron rich side of the valley of stability were studied mainly by combining high resolution (d,p) and (n,γ) reaction results. The ratio of (d,p) cross sections in rotational bands provided evidence for the configuration assignments. Such information is, in general, not available for the neutron-deficient species which now attract the nuclear spectroscopist's interest. However, since the g factors are sensitive to single-particle configurations, they can provide a tool for the identification of configurations.[1,2] Therefore, it is important to thoroughly understand their properties.

It was shown by Kern and Struble[3] that in the deformed region g_R and a linear combination of g_{Ω_p} and g_{Ω_n} can be extracted from measurements of a magnetic moment μ and of an intraband branching ratio λ and/or a multipole mixing ratio δ. These g factors can be predicted from the properties of the even and odd-A neighbors. A survey of the available data showed that in all cases where both μ and λ and/or δ was available, there was an agreement between experimental and predicted g factors in the region of stable deformation.

However, recently[4] an anomaly has been observed for the g factors extracted from the $K=6$ isomeric band in ^{174}Lu. The reason for this has not been determined. One speculation is that it is related to the relatively high K value of that particular band.

In the present paper, we investigate the g factors of the $K^\pi=7^-$ $\{\pi\frac{7}{2}^+[404]+\nu\frac{7}{2}^-[514]\}$ ^{176}Lu ground-state band. Since the K value is even higher than in ^{174}Lu, an anomaly that depends on this parameter should easily be observed.

The ground state magnetic moment has been determined by Brenner *et al.*[5] to be $\mu=+3.1692(45)\mu_N$. We report on the Coulomb excitation of the ground-state band by ^{16}O ion bombardment. From the observed angular distribution and branching ratios, we determine that the g factors of ^{176}Lu do not present an anomaly.

II. EXPERIMENTAL METHOD AND RESULTS

The experiments were performed at SIN/Villigen (Switzerland) using an ^{16}O beam from the variable energy cyclotron. The target was made of a 22.4 mg/cm^2 layer of 99.9% enriched metallic ^{176}Lu deposited on a 1 mm thick thorium backing. Enriched Lu oxide was produced at the Lawrence Livermore National Laboratory. The reduction to metal and the target fabrication were performed at the Oak Ridge National Laboratory. Since thorium was used in the reduction chemistry, there was some contamination of the Lu with this material, and so it was decided to use a thorium backing.

The target was bombarded by 59.5 MeV ^{16}O ions. At this energy the distance of closest approach is 15 fm, implying a minimum distance of 5 fm between the surfaces of the colliding nuclei. This distance is sufficient[6] to avoid the formation of compound nuclei.

Two detectors were used in the experiments: a 6.5 cm^3 intrinsic planar germanium detector having a resolution of 0.56 keV at ^{57}Co, and a 65 cm^3 N type coaxial intrinsic detector having a resolution of 1.0 keV at ^{57}Co and of 1.93 keV at ^{60}Co.

Two experiments were performed, a singles and an angular distribution measurement. In the singles experiment, we observed the photons emitted after Coulomb excitation with the detectors placed at 125° on both sides of the beam line. A precise energy calibration was obtained by observing simultaneously the radiations from ^{182}Ta and ^{192}Ir radioactive sources and the gamma rays from ^{176}Lu in one measurement. The same sources were used for the relative efficiency calibration of the detectors. The energies and intensities of the transitions emitted by the radioactive sources are precisely known.[7]

The singles spectrum observed with the larger detector is shown for illustration in Fig. 1. Five transitions belonging to ^{176}Lu are identified. Their energies and intensities are reported in Table I. They fit into a level scheme extending up to spin $I=10$ (Fig. 2).

The most intense 184.1 keV line is clearly identified as the 8^- to 7^- ground-state transition. Its energy is in agreement with the excitation energy of the $I^\pi=8^-$ level

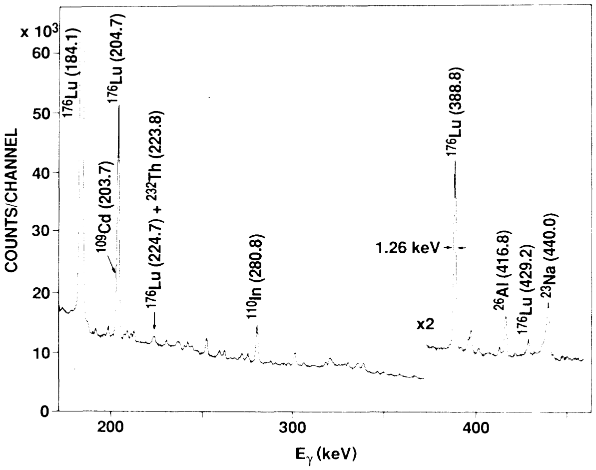

FIG. 1. ^{176}Lu(^{16}O,^{16}O)^{176}Lu spectrum observed at 125° with the larger (65 cm^3) detector.

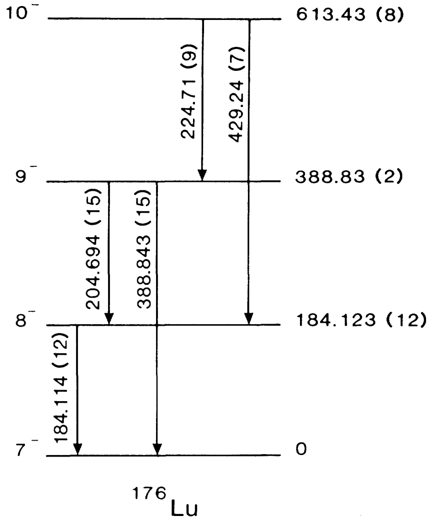

FIG. 2. Scheme of the observed levels in ^{176}Lu.

determined in previous experiments.[8] A $M1$ transition of 184.117(20) keV had been observed by Balodis *et al.*[9] in their study of the ^{175}Lu(n,γ) reaction. However, they placed another transition between the 8^- and 7^- members of the band. Two less intense transitions at 204.7 and 388.8 keV depopulate the next, $I^\pi = 9^-$ level. They, together with the 184.1 keV transition, fulfill the Ritz combination principle. Finally, two fairly weak transitions at 224.7 and 429.2 keV depopulate the $I^\pi = 10^-$ level. They also satisfy the Ritz principle. Figure 1 shows that they have intensities near those of the background lines.

Background lines originate from radioactive radiations in the experimental cave, from reactions on thorium, from other beam correlated sources, and from the activated target. The surrounding activity was measured before and after the experiments with the beam. The thorium peaks are due to Coulomb excitation of the thorium impurities in the target and of the backing by stray ^{16}O particles. These components have been identified in a measurement with the target rotated by 180° (the backing is against the beam). Other peaks associated with the beam have been determined by the same experiment. Some are known to occur in most experiments with oxygen ions, such as the 440.0 keV line from the ^{12}C(^{16}O,αp)^{23}Na reaction. An x-ray fluorescence analysis of the target shows the presence of an important molybdenum contamination. A few peaks, also present in the spectrum of the activated target, are certainly due to reactions on this element, in particular a ^{109}Cd line at 203.7 keV from the decay of ^{109}In and a ^{110}In line at 280.8 keV from the decay of ^{110}Sn (see Fig. 1). It is probable that a number of small peaks observed only on line are due to the prompt decay of compound states formed by reactions on this impurity. The 224.7 and 429.2 keV lines do not belong to recognized background components. It is noteworthy that the 203.7 keV peak from ^{109}Cd occurs close to the 204.7 keV ^{176}Lu line. Although a careful analysis has been done, the error on the intensity of the latter line is somewhat larger than usual.

In the angular distribution experiment, the spectra have been observed with the larger detector at 30°, 42°, 55°, 65°, and 90°. The integral beam charge through the target was monitored by the intensity of the 184.1 keV line observed with the smaller detector located at a fixed position. Dead-time corrections were obtained by comparing the number of gate signals selected by a single-channel analyzer with the sum of the registered events in the gated spectrum.[10] The system isotropy was tested with a radioactive source and found to be good at a level of precision of 0.5%.

TABLE I. Energy, intensity, and normalized angular distribution coefficients for the transitions in ^{176}Lu.

E_γ (keV)	ΔE_γ (eV)	I_γ[a]	ΔI_γ[a]	A_2/A_0	A_4/A_0
184.114	12	1000.	4.		
204.694	15	76.	4.	0.150(14)	0.041(20)
224.71	90	3.0	0.8		
388.843	15	67.9	1.7	0.105(10)	0.012(13)
429.24	70	5.5	0.5		

[a] Relative intensities.

In order to determine the $E2/M1$ mixing ratio δ of an $I \rightarrow I-1$ transition, it is necessary to know, besides its angular distribution, the statistical tensor components ρ_2 and ρ_4 of the initial state. These can be experimentally determined from the angular distribution of a competing pure $E2$ transition. The lines of interest are therefore the 388.8 and 204.7 keV transitions, since the 224.5 and 429.2 keV lines are too weak for a meaningful analysis. The normalized Legendre coefficients obtained are listed in Table I.

III. INTERPRETATION OF THE RESULTS

A. Configuration assignment

The configuration assignment of the $K^{\pi}=7^-$ ground-state band has been established to be $\{\pi\frac{7}{2}^+[404]+\nu\frac{7}{2}^-[514]\}$ (see, e.g., Ref. 8). If we represent the level energies by the formula

$$E(I)=E_0+AI(I+1)+BI^2(I+1)^2 \ , \qquad (1)$$

where $A=\hbar^2/2\mathcal{J}$ is the usual rotation parameter, we obtain from our data $A=12.02$ keV and $B=-0.0040$ keV. The value obtained for $\hbar^2/2\mathcal{J}$ is very close to the one which can be estimated by the simple method proposed by Struble *et al.*,[11] i.e., 11.9±0.2 keV. This not only confirms the configuration assignment but also indicates that the contributions of the single proton and neutron to the moment of inertia can be reliably determined in this case.

B. Analysis of the branching ratios

As shown by Kern and Struble,[3] the formula derived for the magnetic properties of odd-A deformed nuclei can be used for odd-odd species provided we define

$$G^{KK}=[\Omega_p(g_{\Omega_p}-g_R)+\Omega_n(g_{\Omega_n}-g_R)] \ , \qquad (2)$$

where the signs of Ω_p and of Ω_n have to be taken as in the relation $K=\Omega_p+\Omega_n$. G^{KK} can thus be calculated from the branching ratio of two intraband transitions,

$$\lambda=I_\gamma(I\rightarrow I-2)/I_\gamma(I\rightarrow I-1) \ ,$$

by the relation proposed by Boehm *et al.*,[12]

$$\left[\frac{G^{KK}}{Q_0}\right]^2=\frac{K^2}{2.87\times10^5}\frac{E_{\gamma'}^2}{B(I)}\left[\left[\frac{E_\gamma}{E_{\gamma'}}\right]^5\frac{A(I,K)}{\lambda}-1\right] \ , \qquad (3)$$

where $A(I,K)$ and $B(I)$ are geometrical coefficients given in Ref. 12, E_γ and $E_{\gamma'}$ are the energies (in keV) for $I\rightarrow I-2$ and $I\rightarrow I-1$ transitions respectively, and Q_0 is the intrinsic quadrupole moment in units of barns. From our data we obtain the λ values and corresponding $|G^{KK}|/Q_0$ parameters given in Table II.

TABLE II. Branching ratios and corresponding G^{KK}/Q_0 values.

Branching ratios	$\left\lvert\frac{G^{KK}}{Q_0}\right\rvert$
$\lambda_1=\frac{I_\lambda(388.8\text{ keV})}{I_\lambda(204.7\text{ keV})}=0.89(5)$	0.18(1)
$\lambda_2=\frac{I_\lambda(224.7\text{ keV})}{I_\lambda(429.2\text{ keV})}=1.8(5)$	0.19(4)

C. Analysis of the angular distribution

From the experimental angular distribution coefficients of the 388.8 keV line, we deduce that the statistical tensor components $\rho_k(I)$ for the $I=9$ initial level are $\rho_2(9)=-0.28(3)$ and $\rho_4(9)=-0.07(8)$. The $\rho_2(9)$ value is then used to calculate, using the phase convention of Krane and Steffen,[13] the mixing ratio δ for the 204.7 keV transition. We obtain the two solutions $\delta_1=0.54(17)$ and $\delta_2=2.4(4)$. Only the first value is compatible with the branching ratio measurement. Using the relation

$$\frac{G^{KK}}{Q_0}=\frac{0.934\times10^{-3}}{\delta}\frac{KE_\gamma}{(I^2-1)^{1/2}} \ (E_\gamma \text{ in keV}) \ , \qquad (4)$$

we obtain from δ_1 the result $G^{KK}/Q_0=+0.28\pm0.09$ b^{-1}. This result is in agreement with that obtained from the branching ratios. It is less precise but determines the (positive) sign. For our analysis, we will use the average value $G^{KK}/Q_0=+0.18(1)\ \text{b}^{-1}$.

D. Determination of the g factors

With the above result and with $Q_0=7.35(5)$ b as given in Ref. 5, we obtain $G^{KK}=1.32(7)$. The magnetic moment is related to G^{KK} by the formula[3]

$$\mu=g_RI+\frac{K}{I+1}G^{KK} \ . \qquad (5)$$

Inserting the experimental value[5] of $\mu=+3.1692(45)\ \mu_N$ and of G^{KK} in (2) and (5), we obtain

$$g_R=0.288(9) \ , \qquad (6)$$

$$g_{\Omega_p}+g_{\Omega_n}=0.953(3) \ . \qquad (7)$$

E. Comparison with model predictions

The collective g factor g_R^{oo} of the odd-odd system can be predicted[3,4] from the properties of the even and odd-A neighbors:

$$g_R^{oo}=g_R^{ee}-g_R^{ee}\frac{\delta\mathcal{J}_n}{\mathcal{J}_{eo}}+(1-g_R^{ee})\frac{\delta\mathcal{J}_p}{\mathcal{J}_{oe}} \ , \qquad (8)$$

where $\delta\mathcal{J}_p$ and $\delta\mathcal{J}_n$ represent the change in the moment of inertia between the even-even core and the odd-mass nuclei which are isotopic and isotonic with the odd-odd nucleus. According to Henning *et al.*,[14] the magnetic moment of the first excited state in ^{174}Yb is $\mu(2^+)=+0.676(8)$ so that $g_R^{ee}=0.338(4)$. We then calculate, using (8),

$$g_R(^{176}\text{Lu})=0.304\pm0.004 \ . \qquad (9)$$

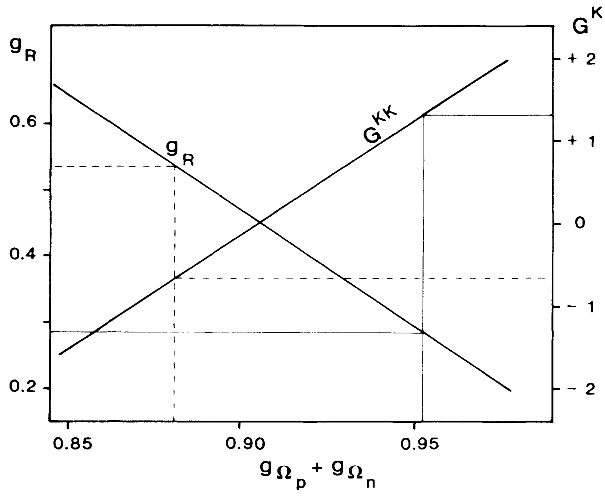

FIG. 3. Dependence of g_R (left-hand scale) and of G^{KK} (right-hand scale) on the value of $g_{\Omega_p}+g_{\Omega_n}$) in ^{176}Lu, assuming $\mu=3.1692\ \mu_N$ (Ref. 5). The dashed lines relate the abscissa values assumed previously[3] with the corresponding g_R and G^{KK} parameters (see text). The continuous lines do the same for the present results.

The small difference, by comparison with the value in (6), cannot be regarded as a discrepancy since no errors in the moments of inertia are taken into account. The experimental value of g_{Ω_p} for the $\frac{7}{2}^+[404]$ configuration[12] in ^{175}Lu is 0.729 ± 0.004. From the value $\mu(\frac{7}{2}^-[514])=+0.7935(6)$ observed for the ^{177}Hf ground state,[15] and from the mixing ratio[16] $\delta(112.95\text{ keV})=-4.7(3)$, we obtain $g_{\Omega_n}=0.218(1)$. The predicted sum $g_{\Omega_p}+g_{\Omega_n}$ is therefore 0.947(4), in excellent agreement with the experimental value in expression (7).

IV. COMMENTS AND CONCLUSIONS

We have to comment on the value $g_R=0.55\pm0.05$ previously obtained by Kern and Struble[3] for ^{176}Lu. Since no branching ratio was then known, they assumed $(g_{\Omega_p}+g_{\Omega_n})$ to be equal to the sum of the g_K factors in ^{175}Lu and ^{177}Hf. Taking published values, they obtained 0.881 for this sum. Figure 3 shows that g_R (left-hand scale) and G^{KK} (right-hand scale) are very sensitive to the value of $(g_{\Omega_p}+g_{\Omega_n})$. The dashed lines indicate the previous[3] and the continuous lines the present values of this sum parameter and the corresponding g_R and G^{KK} values. A small change of 0.071 in $(g_{\Omega_p}+g_{\Omega_n})$ modifies g_R by 0.26, explaining the apparent inconsistency between the previous and present results.

The present work shows that there is no g factor anomaly for the high-K ground-state band in ^{176}Lu. The anomaly observed in ^{174}Lu does not appear, therefore, to be related to the high spin of the 142 d isomeric level. An explanation is still lacking.

ACKNOWLEDGMENTS

The authors wish to thank the crew of the SIN cyclotron, especially S. Drack and Drs. S. Jaccard and Th. Stammbach, for its efficient operation. They thank Dr. V. Ionescu and J. P. Vorlet for their valuable help during the experiments and Dr. G. Galetti for the x-ray analysis of the target. This work was supported in part by the Swiss National Science Foundation, SIN/Villigen, and performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

---

[1] M. F. Slaughter, R. A. Warner, T. L. Khoo, W. H. Kelly, and Wm. C. McHarris, Phys. Rev. C **29**, 114 (1984).

[2] S. Drissi, J.-Cl. Dousse, V. Ionescu, J. Kern, J.-A. Pinston, and D. Barnéoud, Nucl. Phys. **A466**, 385 (1987).

[3] J. Kern and G. L. Struble, Nucl. Phys. **A286**, 371 (1977).

[4] J. Kern, A. Bruder, J.-Cl. Dousse, M. Gasser, V. A. Ionescu, R. Lanners, B. Perny, B. Piller, Ch. Rhême, and B. Schaller, Phys. Lett. **146B**, 183 (1984).

[5] T. Brenner, D. Büttgenbach, W. Rupprecht, and T. Träber, Nucl. Phys. **A440**, 407 (1985).

[6] F. K. McGowan and P. H. Stelson, in *Nuclear Spectroscopy and Reactions*, edited by J. Cerny (Academic, New York, 1974).

[7] *Table of Isotopes*, 7th ed., edited by C. M. Lederer and V. S. Shirley, (Wiley, New York, 1978).

[8] M. M. Minor and R. K. Sheline, Phys. Rev. **187**, 1516 (1969).

[9] M. K. Balodis, J. J. Tambergs, K. J. Alksnis, P. T. Prokofjev, W. G. Vonach, H. K. Vonach, H. R. Koch, U. Gruber, B. P. K. Maier, and O. W. B. Schult, Nucl. Phys. **A194**, 305 (1972).

[10] V. A. Ionescu, J. Kern, C. Nordmann, S. Olbrich, and W. Reichart, Nucl. Instrum. Methods **190**, 19 (1981).

[11] G. L. Struble, J. Kern, and R. K. Sheline, Phys. Rev. **137**, B772 (1965).

[12] F. Boehm, G. Goldring, G. B. Hagemann, G. D. Symons, and A. Tveter, Phys. Lett. **22**, 627 (1966).

[13] S. Krane and R. M. Steffen, Phys. Rev. C **2**, 724 (1970).

[14] W. Henning, G. Bähre, and P. Kienle, Z. Phys. **241**, 138 (1971).

[15] S. Büttgenbach, M. Herschel, G. Meisel, E. Schrödel, and W. Witte, Phys. Lett. **43B**, 479 (1973); Z. Phys. **260**, 157 (1973).

[16] H. Ernst, E. Hagn, E. Zech, and G. Eska, Phys. Rev. B **19**, 4460 (1979), and references therein.