Angular correlation and nuclear orientation study of ^{131}I populated in the decay of ^{131}Te^m

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Some additional levels are proposed in the decay scheme of ^{131}Te^m. From angular correlation and nuclear orientation measurements the spin and parity of several levels are determined uniquely: 774 keV ($\frac{11}{2}^+$), 852 keV ($\frac{9}{2}^+$), 1060 keV ($\frac{9}{2}^+$), 1315 keV ($\frac{9}{2}^+$), 1556 keV ($\frac{15}{2}^+$), 1596 keV ($\frac{13}{2}^+$), 1646 keV ($\frac{11}{2}^-$), 1797 keV ($\frac{15}{2}^-$), 1899 keV ($\frac{13}{2}^-$), 1980 keV ($\frac{11}{2}^-$), and 2001 keV ($\frac{9}{2}^\pm$ or $\frac{11}{2}^+$). The $\delta(E2/M1)$ ratios for the different transitions are obtained. The magnetic moment of the ^{131}Te isomeric state is derived: $\mu = (-1.04 \pm 0.04)\mu_N$.

[RADIOACTIVITY ^{131}Te^m from ^{130}Te(n, γ); measured $\gamma\gamma(\theta)$, $I_\gamma(\theta, T)$. ^{131}I deduced J, n, $\delta(E2/M1)$; ^{131}Te^m deduced μ. Ge(Li) detectors.]

I. INTRODUCTION

Very recently several theoretical calculations have been carried out on odd iodine isotopes. In these calculations the coupling of a three proton cluster to the quadrupole vibrational field is considered.[1-3] In general this model gives a better account of the complexity of the experimental spectra than the simpler quasiparticle plus phonon calculations.[4] Although quite a lot of systematic data are available concerning the 125, 127, and 129 iodine isotopes, the spectrum of ^{131}I is not known so well.[5-8] This is mainly due to the large number of γ rays occuring in the decay of ^{131}Te which has a high Q value. An interesting feature of the I level scheme is the occurence of odd parity states; their existence follows without ambiguity from the $E1$ transitions which were measured by electron conversion.[6,7] One of these levels at 1797 keV has a long lifetime (6 nsec); its spin value is important since this level is a good candidate for quadrupole moment measurements. For spin and multipolarity determination we have used angular correlation measurements as well as nuclear orientation measurements. As we have already shown in a previous work,[9] the combination of both measurements is very useful to resolve ambiguities which could follow from one type of measurement only. Indeed the angular correlation measurement often involves cascades in which a γ ray of mixed multipolarity (L, L') between levels (I_1, I_2) is the first transition; in the expression for the angular correlation the nuclear parameters will enter in a combination $B_K(I_1, I_2, L, L')$. The nuclear orientation measurement will give these same parameters in a combination $A_K(I_1, I_2, L, L')$, which is different.

II. DECAY SCHEME OF ^{131}Te^m

The decay scheme of ^{131}Te^m has been studied by Beyer, Kelly, and Berzins.[7,8] However a direct spectrum measurement as well as coincidence measurements with two Ge(Li) detectors show several discrepancies in their proposed scheme. First of all there is a large number of transitions which were not reported in their work. Also some transitions connecting the high energy levels (above 1.8 MeV) were not properly situated. In Fig. 1, we show a spectrum which is compatible with our experimental data. A more complete study of the decay scheme has been reported by Jackson, Walters, and Meyer.[10] For simplicity we have redrawn in Fig. 2 all the data concerning the angular correlation and nuclear orientation studies reported here.

III. ANGULAR CORRELATION MEASUREMENT

A. Source

^{131}Te^m was prepared by n-γ reaction on enriched metallic ^{130}Te. A 24 h irradiation was done at the BR2 reactor Mol with a flux of 1.8×10^{14} n/cm^2. A chemical treatment was needed to remove the ^{131}I coming mainly from the decay of 25 min ^{131}Te.[5] Our samples were solutions of ^{131}Te in hydrochloric acid, in a 2 mm × 10 mm cylindrical container.

B. Apparatus

Our correlation apparatus has three moveable Ge(Li) detectors (Philips 30 cm^3, 2.8 keV at 1.33 MeV). The correlation was measured between two pairs of detectors simultaneously. The coincidence circuit consists of three fast discriminators

(Canberra EZS 1426) which feed two time to amplitude converters (TAC) for each pair of coincidences. On the output of the TAC's two pairs of single channel windows are set up for the real coincidences and for the chance coincidences. The output of the single channel analyzers are sent to a gating system which (a) opens the gates of the corresponding analog to digital converters (ADC) and (b) signals the data acquisition system when the ADC's have terminated their conversion. The data acquisition system is a PDP8*L* 8192 word minicomputer. For each coincidence event the energy of both γ rays is analyzed by the computer program which checks if the energy falls within one of 22 selected (software) windows. Such events are stored in a 22 by 22 matrix. The time of analysis is of the same order as the conversion time in the ADC's (about 50 μsec). Chance coincidences are analyzed the same way but only the sum of the events is stored.

C. Measurement and results

We have measured coincidences between the peaks at 81, 102, 201, 241, 334, 774, 782, 794, 823, 910, 921, 1060, 1125, 1149, and 1207 keV. Windows on these peaks, as well as side windows for background corrections were selected as shown in Fig. 3. The coincidences were measured at the angles 90, 120, 135, and 180° between the two pairs of detectors. The measured coincidence numbers were corrected for centering errors (less than 1%), and for chance coincidences (about 1%). Background corrections were made as described in Ref. 11. The results of a fit through these points of

$$W(\theta) = A_{00}[1 + A_{22}Q_{22}P_2(\cos\theta) + A_{44}Q_{44}P_4(\cos\theta)] \quad (1)$$

are given in Table I. Q_{KK} are the solid angle correction coefficients and P_K are Legendre polynomials.

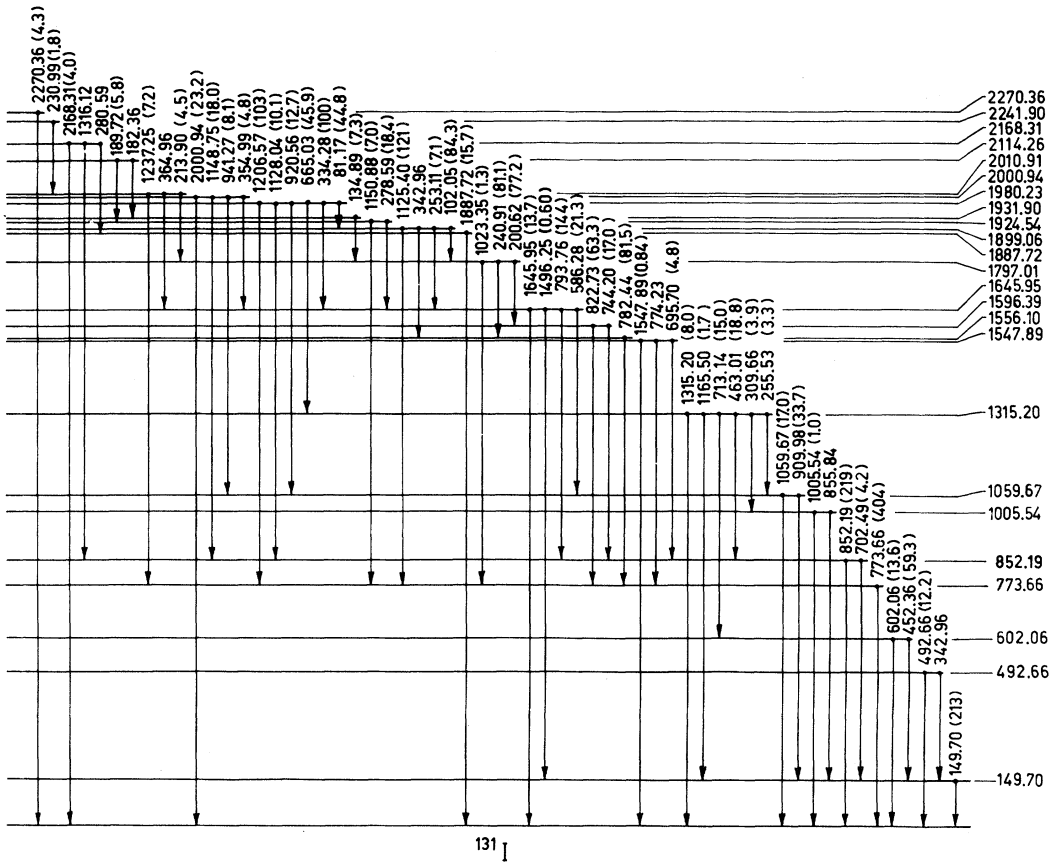

FIG. 1. Decay scheme of $^{131}Te^{m}$ deduced from a direct spectrum measurement and from coincidence measurements. The error on the level energies is less than 40 eV. The transition energies indicated are the computed energy differences between these levels. The error on the reported intensities is less than 5 on the last figure.

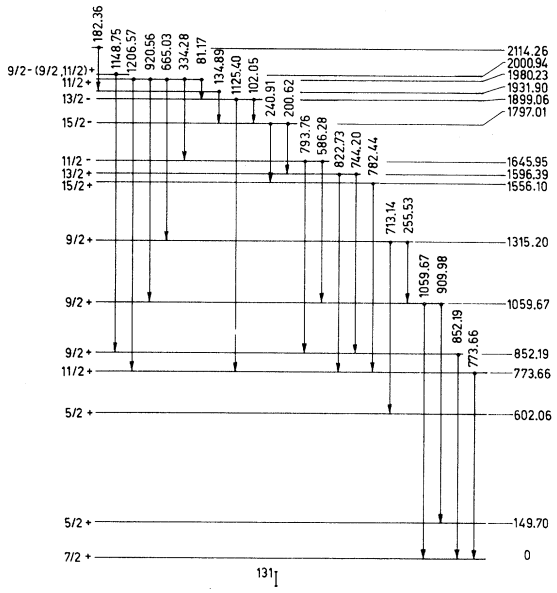

FIG. 2. Part of the decay scheme of $^{131}Te^{m}$ showing the levels and transitions considered in our angular correlation orientation measurements. Spin and parity values are as deduced in this work.

D. Analysis

The A_{KK} coefficients in (1) are given by

$$A_{KK} = B_K(1) U_K(i) A_K(2) , \qquad (2)$$

where $B_K(1)$ depends on the spin values and multipolarity of the first transition and A_K depends on the last transition. The U_K coefficient accounts for nonobserved intermediate radiation when it occurs. The 201 and 241 keV transitions have a pure $E1$ character.[6,7] Using the (201-822) and the (241-782) correlation coefficients we can calculate (for a given spin sequence) the mixing ratios of the 782 and 823 keV transitions. These values and the (823-774) and (782-774) correlation coefficients should give the same value for the $A2$ value of the 774 keV transition. This condition restricts the possible spin values for the 1797, 1596, 1556, and 774 keV levels. In a similar way the calculation was extended to the 1899 keV level (using the 102 and 1125 keV transitions) and to the 1980 keV level (using the 81 and 1207 keV transitions). The following spin sequence was deduced 1980 $(J-2)$, 1899 $(J-1)$, 1797 (J), 1596 $(J-1)$, 1556 (J) and 774 $(J-2)$; $J = J$ (1797) can take the

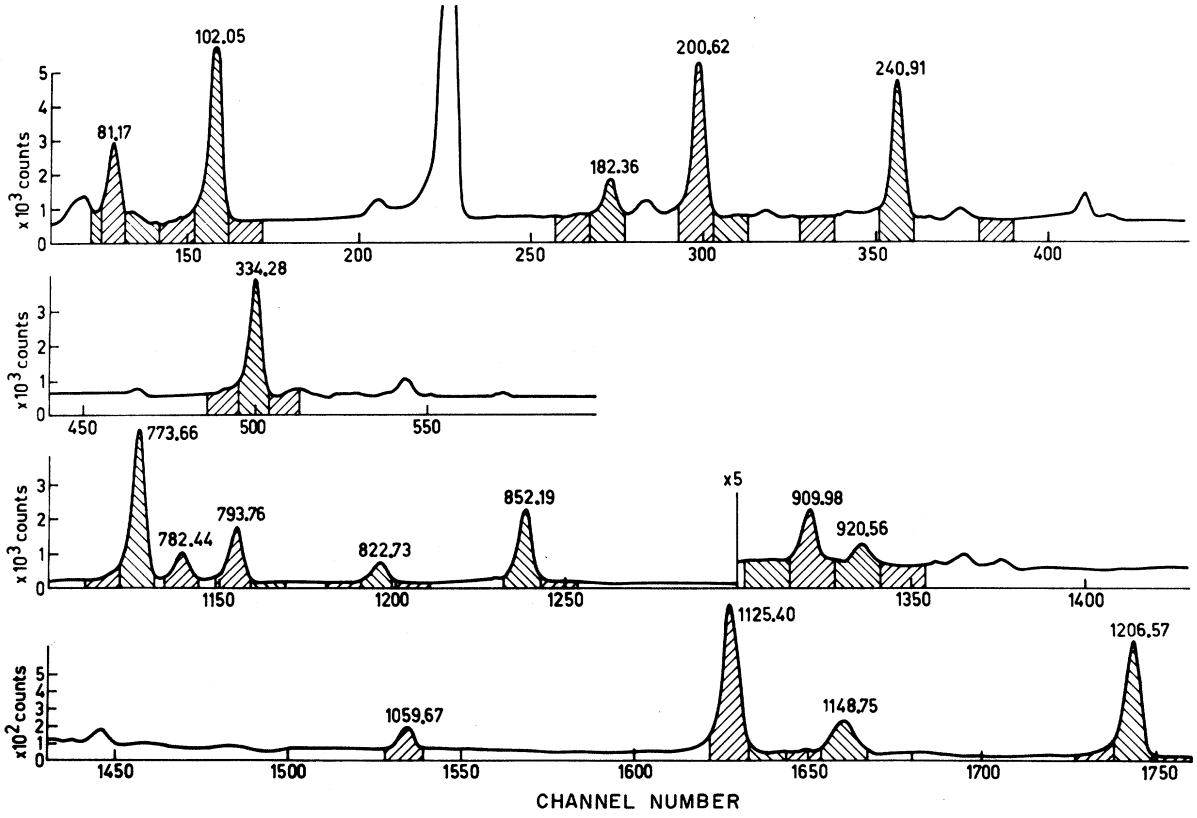

FIG. 3. Part of the direct γ spectrum of $^{131}Te^{m}$ indicating the windows chosen in the angular correlation measurement.

TABLE I. Experimental A_{22} and A_{44} values resulting from a fit through the experimental data of $W(\theta) = A_{00}[1 + A_{22}Q_{22}P_2(\cos\theta) + A_{44}Q_{44}P_4(\cos\theta)]$. The calculated A_{22} and A_{44} values are with spin values given in the level scheme and δ values given in Table III.

Correlation (keV)		A_{22} (Exp.)	A_{44} (Exp.)	A_{22} (Calc.)	A_{44} (Calc.) [a]
81	102	0.043 ± 0.011	0.011 ± 0.017	0.032 ± 0.003	
81	201	0.081 ± 0.012	−0.019 ± 0.018	0.062 ± 0.004	
81	241	−0.097 ± 0.012	−0.029 ± 0.019	−0.103 ± 0.007	
81	774	−0.086 ± 0.012	0.007 ± 0.018	−0.091 ± 0.007	
81	782	−0.115 ± 0.028	−0.017 ± 0.042	−0.085 ± 0.006	
81	823	0.139 ± 0.031	−0.049 ± 0.047	0.202 ± 0.014	
82	1125	0.108 ± 0.024	−0.048 ± 0.035	0.068 ± 0.007	
102	201	0.056 ± 0.005	0.010 ± 0.007	0.059 ± 0.004	
102	241	−0.096 ± 0.004	−0.014 ± 0.007	−0.098 ± 0.007	
102	774	−0.087 ± 0.006	0.020 ± 0.009	−0.081 ± 0.006	
102	782	−0.078 ± 0.009	−0.005 ± 0.013	−0.081 ± 0.006	
102	823	0.195 ± 0.010	−0.020 ± 0.014	0.192 ± 0.014	
183	201	0.050 ± 0.029	−0.013 ± 0.043	0.064 ± 0.011	b
183	241	−0.072 ± 0.032	0.000 ± 0.048	−0.106 ± 0.018	b
183	774	−0.045 ± 0.042	−0.006 ± 0.062	−0.088 ± 0.015	b
183	782	−0.175 ± 0.062	0.039 ± 0.094	−0.088 ± 0.015	b
183	823	0.282 ± 0.060	−0.031 ± 0.083	0.205 ± 0.036	b
201	774	−0.062 ± 0.006	0.003 ± 0.009	−0.070 ± 0.000	
201	823	0.161 ± 0.006	−0.008 ± 0.009	0.162 ± 0.003	
241	774	0.166 ± 0.006	−0.010 ± 0.008	0.172 ± 0	
241	782	0.182 ± 0.006	−0.006 ± 0.008	0.172 ± 0	
334	794	−0.130 ± 0.008	0.045 ± 0.014	−0.148 ± 0.001	
334	852	−0.537 ± 0.010	0.053 ± 0.013	−0.505 ± 0.012	−0.016 ± 0.016
782	774	0.120 ± 0.008	0.003 ± 0.011	0.102 ± 0	0.009 ± 0
823	774	−0.310 ± 0.009	0.018 ± 0.013	−0.307 ± 0.006	−0.008 ± 0.001
1125	774	−0.072 ± 0.008	0.009 ± 0.011	−0.071 ± 0	
1207	774	0.182 ± 0.010	−0.035 ± 0.016	0.182 ± 0	
852	794	0.167 ± 0.010	−0.010 ± 0.012	0.170 ± 0.004	
1149	852	−0.315 ± 0.050	−0.037 ± 0.045	−0.475 ± 0.075	0.000 ± 0.002 [c]
921	910	0.128 ± 0.084	0.062 ± 0.110	−0.071 ± 0	
921	1060	−0.114 ± 0.086	−0.195 ± 0.117	−0.133 ± 0.021	

[a] The not reported A_{44} values are zero within 0.001.

[b] Using $B_2(183)U_2(135) = 0.235 \pm 0.041$; $B_4(183)U_4(135) = -0.016 \pm 0.059$.

[c] The calculated value is for the hypotheses $J^\pi(2001) = \frac{9}{2}-$ and $\delta = 0.006$. The other hypotheses (Table III) give the same result within a few percent.

values $\frac{11}{2}$, $\frac{13}{2}$, or $\frac{15}{2}$. Use was made of the fact that the 81 keV transition is mainly $M1$.[6,7] This result was used as a starting point for a least squares fit where the χ^2 was defined as

$$\chi^2(\delta_1, \delta_2 \ldots \delta_9) = \sum_{k=2,4} \frac{\sum_{ij}[A_{KK}^{\exp}(i,j) - A_{KK}^{\text{calc}}]^2}{\sigma^2(A_{KK}^{\exp})},$$

where the parameters stand for the mixing ratios of the involved transitions: 81, 102, 201 ($\delta = 0$), 240 ($\delta = 0$), 773, 783 ($\delta = \infty$), 823, 1125, and 1207 keV. The summation (i,j) extended to all measured correlations involving these transitions. From this fit, however, no definite choice could be made between J (1797) = $\frac{11}{2}$, $\frac{13}{2}$, or $\frac{15}{2}$.

In the same way we analyzed the 334-794-852 keV cascade connecting the 1980 keV level to the 1646, the 852 keV, and the ground state level ($\frac{7}{2}^+$). The existence of a transition to the $\frac{5}{2}^+$ (150 keV) level limits $J(1646)$ to values $\leq \frac{11}{2}$. Only two possible solutions were found both with $J(852) = \frac{9}{2}$ and $J(1646) = \frac{11}{2}$. One solution with $A_2(852) > 0$ allows spin values $J(1980) = \frac{9}{2}, \frac{11}{2}, \frac{13}{2}$. The other one corresponds to $A_2(852) < 0$ and allows $J(1980) = \frac{9}{2}$ or $\frac{13}{2}$. Combining this with the above values of $J(1797) = J(1980) + 2$ we deduce $J(1797) = \frac{13}{2}$ or $\frac{15}{2}$. This result is consistent with the logft values from the decay of the $\frac{11}{2}$ - ^{131}Te^m state.[7] A $J(1797)$

$= \frac{11}{2}$ value would lead to $J(1980) = \frac{7}{2}$ which should give larger logft values than the 6.1 measured.

Thus from our angular correlation measurement it was not possible to resolve the ambiguity concerning the $J(1797)$ value; therefore a nuclear orientation measurement was necessary.

The 183 keV transition connects levels at 2115 and at 1932 keV. This level decays via a 135 keV transition to the 1797 keV level. From our measurements we deduce the coefficients $B_K(183)$ $U_K(135)$ which are consistent with a $\Delta J = \pm 1$ transition and small $\delta(E2/M1)$ ratio.

IV. THE NUCLEAR ORIENTATION MEASUREMENT

A. Experimental setup and source preparation

The nuclear orientation measurement was performed using a high-power ^{3}He-^{4}He dilution refrigerator. The γ radiation was detected with 30 cm^3 Ge(Li) detectors at 0 and 90° with respect to the field direction. A detailed description of the apparatus and the experimental method is given in Ref. 12. The temperature down to 14 mK was monitored by the anisotropy of the 135 keV ^{57}Co transition. The source used was produced after irradiating 20 mg of metallic enriched ^{130}Te in the 1.8×10^{14} n/cm^2 neutron flux of the BR2 reactor at Mol. After a chemical treatment to discard ^{131}I, ^{131}Te was implanted in a thin iron foil using the isotope separator of our institute. 0.7×10^{13} particles/cm^2 were implanted at 75 kV.

B. Results and analysis

Magnetic moment of the $\frac{11}{2} = \mathrm{Te}^{(m)}$ state

The angular distribution of a γ transition is described by

$$W(\theta, T) = 1 + \sum_{2,4} B_K(\mu B/T) U_K A_K Q_K P_K(\cos\theta) . \tag{3}$$

$B_K(\mu B/T)$ describes the orientation of the mother nucleus. U_K accounts for nonobserved transitions, including the β transition. A_K, Q_K, and P_K have the same meaning as in the angular correlation analysis.

Given the anisotropy $W(0)/W(90) - 1$ as a function of temperature a fitting procedure gives us the magnetic moment of the mother nucleus provided the $U_K A_K$ values are known, or conversely. We have first analyzed the 201, 241, 782, 823, and 1207 transitions. Using A_K and δ values deduced from the correlation fit, the β decay branching ratios from Ref. 7, assuming a $10 \pm 10\%$ Fermi admixture in the allowed β transitions and neglecting the others, we calculate the $U_K A_K$ quantities for both $J(1797) = \frac{13}{2}$ and $\frac{15}{2}$. In fact the difference between both cases is small compared to the experimental errors. So we could use mean $U_K A_K$ values to obtain a μB value 0.349 ± 0.013 $\times 10^{-24}$ J. Assuming a hyperfine value of the magnetic field at the nucleus 65.7 ± 2.0 T[13] this corresponds to a μ value $(-1.05 \pm 0.05)\mu_N$.

TABLE II. Experimental U_2A_2 values compared to the calculated values.

Energy (keV)	U_2A_2 (Exp.)	U_2A_2 [a] (Calc.)	U_2 [b]	Multipolarity
201	0.183± 0.020	0.246± 0.001	0.912± 0.004	$E1$
241	−0.368± 0.019	−0.406± 0.002	0.912± 0.004	$E1$
334	−0.272± 0.017	−0.267± 0.163	0.924± 0.010	$(M1, E2)$
586	0.202± 0.089	0.246± 0.002	0.854± 0.010	$E1$
665	0.273± 0.040	0.266± 0.003	0.924± 0.010	$E1$
713	−0.29 ± 0.12	−0.380± 0.004	0.878± 0.004	$E2$
744	−0.349± 0.081	−0.352± 0.001	0.886± 0.004	$E2$
782	−0.434± 0.024	−0.336± 0.001	0.868± 0.004	$E2$
794	0.230± 0.015	0.246± 0.002	0.854± 0.010	$E1$
823	0.773± 0.026	0.799± 0.015	0.886± 0.004	$(M1, E2)$
852	0.824± 0.014	$0.873^{+0.015}_{-0.061}$	0.802± 0.014	$(M1, E2)$
910	−0.351± 0.051	−0.357± 0.006	0.825± 0.013	$E2$
921	0.49 ± 0.13	0.266± 0.003	0.924± 0.010	$E1$
1060	−0.657± 0.057	−0.669± 0.334	0.825± 0.013	$(M1, E2)$
1207	−0.434± 0.016	−0.409± 0.004	0.924± 0.010	$E1$

[a] The δ values derived from the angular correlation measurements were used. For the $E1$ cases δ was taken equal to zero.

[b] U_2 values derived using all the known data concerning branching ratios (Beyer *et al.*, Refs. 7 and 8), our measurement (Fig. 1), and multipolarities. The $\frac{11}{2}^- \frac{11}{2}^-$-$\beta$ decay was supposed to be pure Gamov-Teller with 0.1 ± 0.1 fm admixture. Errors include uncertainties concerning spin and multipolarity.

Spin and δ values

This μ value was used to determine the $U_K A_K$ of the transitions reported in Table II. We have used these to continue our analysis. First we note that the A_2 value for the 852 keV transition is positive. Then, using the results for the 334, 794, and 852 keV correlations, we deduce that the 794 keV transition has a small δ value. This agrees with a $E1$ character of this transition. Indeed, the 334 keV transition has a mixed $E2+M1$ nature[6,7] and thus the 1646 keV level has negative parity (as the 1980 keV level).

The analysis of the 334 keV distribution leads to the values $J(1980)=\frac{9}{2}, \frac{11}{2}$ as previously deduced from the angular correlation data. The best fit is obtained for the $\frac{11}{2}$ value.

The 586 and 910 keV transitions lie between the 1646($\frac{11}{2}^-$), 1060, and the 150 keV ($\frac{5}{2}^+$) levels. One of these transitions has to be pure $E2(\Delta J=2)$; only $J(1060)=\frac{9}{2}$ agrees with the observed $A_2(586)$ and $A2(910)$. This solution is consistent with a pure $E1$ character of the 586 keV transition and a pure $E2$ character of the 910 keV transition. This indicates that the 1060 keV state has positive parity. This is confirmed by the $A2$ value of the 1060 keV transition which indicates that this transition has a mixed $E2+M1$ character ($\delta=1.2^{+0.9}_{-0.5}$).

The 921 keV transition, connecting the 1980 keV ($\frac{9}{2}^-, \frac{11}{2}^-$) and the 1060 keV ($\frac{9}{2}^+$) level, has to be pure $E1$ according to the parity change. The experimental $A2(921)$ value only gives a small mixing ratio if we assume $J(1980)=\frac{11}{2}$. This resolves the ambiguity, $J(1797)=\frac{15}{2}$.

Next we consider the 665 and 713 keV transitions connecting the 1980 ($\frac{11}{2}^-$), 1315, and the 602 ($\frac{5}{2}^+$) levels. These are analyzed in the same way as the 586 and 910 transitions. We deduce $J(1315)=\frac{9}{2}^+$, the 665 transition being pure $E1$, the 713 pure $E2$.

Finally, using $A2(852)$ and the $A22$ value from the angular correlation measurement, we deduce $B2(1149)$. Two spin values, $\frac{11}{2}$ or $\frac{9}{2}$, for the 2001 keV level could give this value. If $J(2001)$ is $\frac{11}{2}$ we could obtain this value only for large $\delta(E2/M1)$ mixing ratios (Table III), which would indicate positive parity for the 2001 keV state. If $J(2001)$ is $\frac{9}{2}$ a solution with $\delta=0$ is possible; this would allow negative parity. On the other hand there is an important β feeding to the 2001 keV state from $^{131}Te^m$ ($\frac{11}{2}^-$), $\log ft=6.6$. This seems to indicate that the transition is allowed and favors the solution $J^\pi(2001)=\frac{9}{2}^-$.

V. DISCUSSION

We have obtained from our measurements unique spin and parity assignments for several levels: 774 ($\frac{11}{2}^+$), 852 ($\frac{9}{2}^+$), 1060 ($\frac{9}{2}^+$), 1315 ($\frac{9}{2}^+$), 1556 ($\frac{15}{2}^+$), 1596 ($\frac{13}{2}^+$), 1646 ($\frac{11}{2}^-$), 1797 ($\frac{15}{2}^-$), 1889 ($\frac{13}{2}^-$), 1980 ($\frac{11}{2}^-$), and 2001 keV ($\frac{9}{2}^\pm$ or $\frac{11}{2}^+$). The $\delta(E2/M1)$ mixing ratios for the considered transitions are summarized in Table III. Using these values we have recalculated the A_2 and A_{22} values for comparison with the measured data. As seen in Tables I and II they compare very favorably. The disagreement for the 920-910 keV correlation could be ascribed to the very poor statistics.

The obtained spin values below 1 MeV fit very well in the systematics of the odd-mass iodine isotopes. A comparison with the model calculations is given by Almar, Civitarese, and Krmpotic (Ref. 3); the spin values of the 774 and 852 keV state ($\frac{11}{2}^+, \frac{9}{2}^+$) are as predicted. The higher spin states ($\frac{13}{2}^+$ and $\frac{15}{2}^+$) are not obtained from these calculations, neither are the negative parity levels considered by these authors.

The lowest negative parity state is the $\frac{11}{2}^-$ state at 1646 keV. This is in agreement with the predictions of Paar.[2] According to Ref. 2 this state is to be interpreted as a $h_{11/2}$ single particle state. Indeed the $M2(E3)$ transition (1646 keV) and the $E3$ transition (1496 keV) the the ground state ($g_{7/2+}$) and the first excited state ($d_{5/2}$) are intense compared to the $E1$ transitions to the $\frac{9}{2}^+$ states at 852, 910, and 1060 keV. The higher negative parity levels should be seniority 3 states; however, no description of these levels is given. This would seem particularly useful for the $\frac{15}{2}^-$ state at 1797 keV. This level has a lifetime of 5.9 ± 0.2 nsec and was previously ascribed a

TABLE III. $(E2/M1)$ mixing ratios resulting from the angular correlation and the nuclear orientation measurements. For the spin values of the 1932, 2001, and 2115 keV levels several possibilities are left open. The convention for δ is that of Krane and Steffen, Phys. Rev. C 2, 724 (1970).

Energy (keV)	$\delta(E2/M1)$	
81	-0.022 ± 0.009	
102	-0.028 ± 0.003	
183	$-0.05\ \pm0.03$	$J(1932)=J(2115)+1$
	$-0.02\ \pm0.03$	$J(1932)=J(2115)-1$
334	-0.233 ± 0.027	
823	-0.413 ± 0.016	
852	$-1.20\ \pm0.09$	
	$-0.580^{+0.044}_{-0.057}$	
1060	$1.2^{+0.9}_{-0.5}$	
1149	0.006 ± 0.097	$J(2001)=\frac{9}{2}(\pi=\pm)$
	-0.828 ± 0.086	$J(2001)=\frac{9}{2}(+)$
	0.520 ± 0.086	$J(2001)=\frac{11}{2}(+)$
	$1.68\ \pm0.25$	$J(2001)=\frac{11}{2}(+)$

$\frac{11}{2}^-$ character.[6,14] It is a good candidate for momentum measurements through perturbed angular correlations.

Finally using all the obtained data we have recalculated, the magnetic moment of $^{131}Te^m$, $\mu = (-1.04 \pm 0.04)\mu_N$. This value is very close to the values reported in Ref. 12 for the other odd-mass Te isomers. Including this value in the already measured values no systematic trend of the magnetic moment with mass number is observed.

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