Decay of $I^{130} \rightarrow Xe^{130}$

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The decay of I^{130} has been previously studied by two groups of workers, and, as a result, the following level scheme for Xe^{130} has been proposed: 528 kev (2^+), 1190 kev (4^+), 1930 kev (6^+), and 2340 kev (5^-). Only the states at 1930 kev and 2340 kev were found to be directly populated by beta decay. However, the recent measurement of spin 5 for I^{130} suggests that the 1190-kev state, if 4^+, should be populated by beta decay. In the present work, such a group was looked for and not found. A lower limit of 9.8 was set for the log *ft*. Gamma-gamma correlations were also measured. The experimental correlation for 1190-528-0 level sequence can be fitted by $4(Q)2(Q)0$ or by $2(96\%D+4\%Q)2(Q)0$ sequences. The 2^+ assignment to the 1190-kev level requires a predominantly $M1$ transition for the 2^+ to 2^+ transition in contrast to the predominantly $E2$ character of other known transitions of this type. Therefore, either 4^+ or 2^+ assignment to the 1190-kev state leads to an anomalous situation. Six other angular correlations were measured in an attempt to determine the characteristics of the levels at 1930 kev and 2340 kev. It was not possible to obtain unique assignments.

INTRODUCTION

THE beta and gamma rays emitted in the decay of I^{130}, $t_{\frac{1}{2}}=12.5$ hours, were first studied by Roberts, Elliott, Downing, Peacock, and Deutsch.[1] This group found two beta groups with energies of 1.03 and 0.61 Mev and four gamma rays with energies of 417, 536, 667, and 714 kev. It was assumed, on the basis of beta group energy differences, that the 417-kev gamma followed the 0.61-Mev beta group decay. The three remaining gamma rays are all in cascade and their order of emission was not determined. Caird and Mitchell[2] have also studied this decay. They used a lens spectrometer to measure both the continuous electron spectrum and the internal conversion electron lines, and the photoelectrons ejected by the gamma rays in lead and uranium radiators. Gamma-gamma coincidence measurements were also made using NaI detectors. In addition to the radiations found by Roberts *et al.*, Caird and Mitchell found a 1150-kev gamma ray. The latter group proposed the level scheme shown in Fig. 1. The position of the 536-kev transition has been verified by Coulomb excitation of the 536-kev level.[3]

Since Sherwood and Ovenshine at Oak Ridge National Laboratory were engaged in making a direct determination, by atomic beam techniques, of the ground-state spin of I^{130},[4] it seemed desirable to have additional information on the decay of this nucleus. We wish to report information obtained from gamma-gamma correlation measurements. Relative gamma-ray intensities and coincidence results are also given. Limits are determined for the intensities of possible higher energy β-groups.

APPARATUS AND SOURCE

The singles gamma-ray spectrum was measured with a thallium-activated NaI crystal, 3 inches in diameter and 3 inches long, mounted on a DuMont type 6363 photomultiplier tube. Data were taken with a 120-channel analyzer of Bell-Kelley design.[5] For the coincidence and angular correlation experiments two 3 in. $\times 3$ in. NaI crystals were used. A single-channel analyzer was used to set a window over one of the gamma photopeaks and the coincident gamma pulses were displayed on the 120-channel analyzer. The coincidence circuit used was of the fast-slow type. The resolving

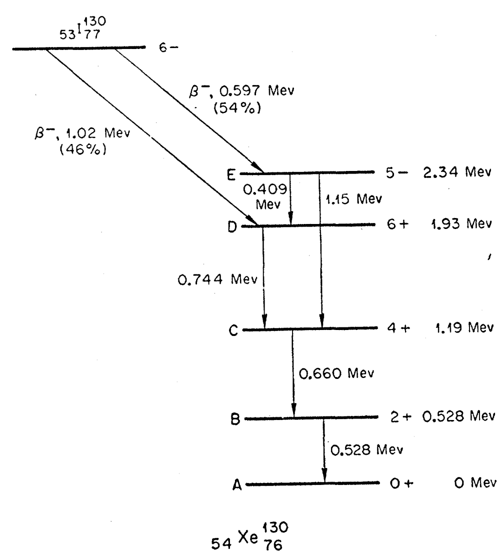

FIG. 1. Level scheme of Caird and Mitchell.[2]

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[1] Roberts, Elliott, Downing, Peacock, and Deutsch, Phys. Rev. **64**, 268 (1943).

[2] R. S. Caird and A. C. G. Mitchell, Phys. Rev. **94**, 412 (1954).

[3] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956); Pieper, Anderson, and Heydenburg, Bull. Am. Phys. Soc. Ser. II, **3**, 38 (1958).

[4] Nuclear spin of I^{130} is 5. J. E. Sherwood and S. J. Ovenshine, Bull. Am. Phys. Soc. Ser. II, **3**, 371 (1958). This spin has also been determined to be 5 by Garvin, Green, and Lipworth, Phys. Rev. Lett. **1**, 292 (1958).

[5] P. R. Bell and G. Kelley, Oak Ridge National Laboratory Report ORNL-1620, September 10, 1953 (unpublished); and Oak Ridge National Laboratory Report ORNL-1975, September 10, 1955 (unpublished).

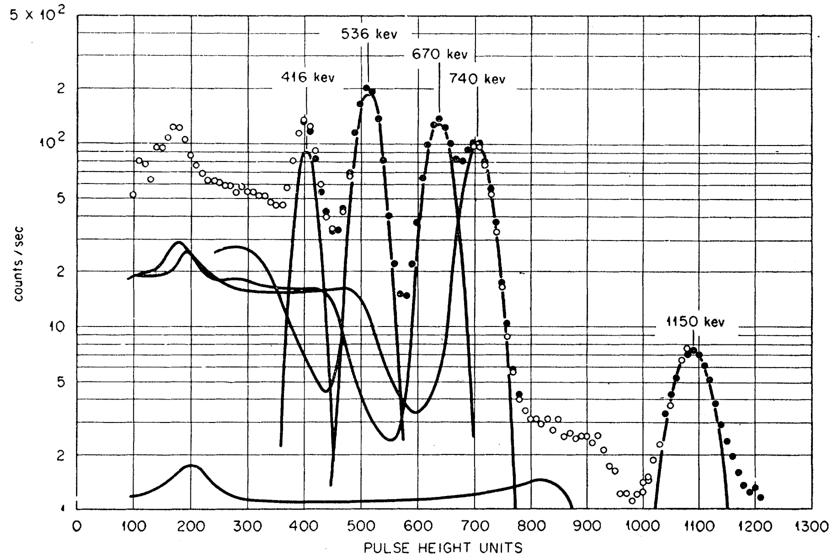

FIG. 2. I^{130} singles gamma-ray spectrum at $h=20$ cm.

time is fixed by a pulse shaping delay line and $2\tau=0.225 \times 10^{-6}$ sec. Source to crystal distances used were 15, 12, and 10 cm. Lucite absorbers were used to prevent beta rays from striking the crystals.

The I^{130} was produced by slow neutron irradiation of $I^{129}(t_{\frac{1}{2}}\sim 2\times 10^7$ yr) in the LITR at Oak Ridge.[6] The I^{129} used in this work was kindly supplied by the Isotopes Division of Oak Ridge National Laboratory.

EXPERIMENTAL RESULTS

The singles gamma-ray spectrum of I^{130} is shown in Fig. 2. The source to detector distance was 20 cm. The spectrum was decomposed as indicated into five gamma rays. The results are given in Table I.

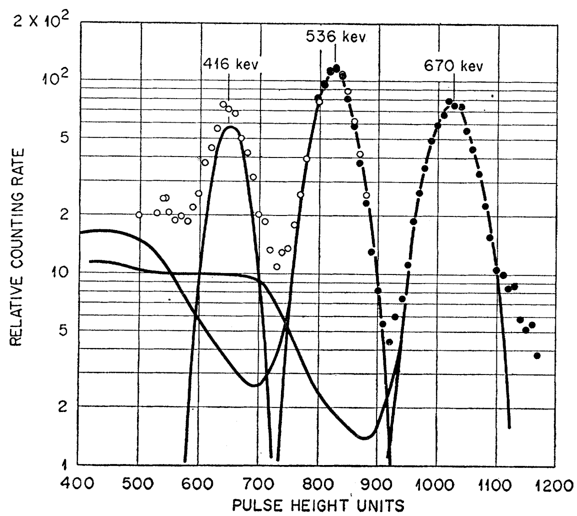

FIG. 3. Gamma-ray spectrum in coincidence with 740-kev gamma (from angular correlation measurement).

[6] We are indebted to J. E. Sherwood and S. J. Ovenshine for their assistance in making the I^{129} neutron irradiation.

An upper limit for the intensity of a crossover in competition with the 740–670 kev cascade was estimated to be 1% of the 536-kev gamma-ray intensity. The upper limit for a crossover in competition with the 670–536 kev cascade was estimated to be 4% of the 536-kev gamma intensity.

The gamma-ray intensity measurements indicate that only the third and fourth excited states are populated by beta decay; in agreement with the results of Caird and Mitchell. The relative beta decay population to the third and fourth excited states, as determined from the gamma intensities, is 0.53 ± 0.06, log $ft=6.5$ and 0.47 ± 0.06, log $ft=5.7$, respectively.

An anthracene crystal, $1\frac{1}{2}$-in. diameter by $\frac{3}{4}$ in. thick, scintillation spectrometer was used to set an upper limit of the intensity of a possible beta group directly populating the second excited state. No electrons of such a group, after background correction, were detected. A lower limit of 9.8 can be set for the log ft value of this transition. (The lower limit for log ft values of possible beta transitions to the first excited and ground states would be greater than 9.8.)

The gamma-ray intensities determined in the present study disagree somewhat with those obtained by Caird and Mitchell. By using the K-shell internal conversion electrons per disintegration data of Caird and Mitchell, new K-shell conversion coefficients can be calculated. These results are given in Table II.

TABLE I. Gamma-ray energies and intensities.

E_γ (kev)	Relative intensity
416 ± 6	0.35 ± 0.014
536 ± 8	1.00
670 ± 10	0.99 ± 0.05
740 ± 11	0.88 ± 0.05
1150 ± 18	0.13 ± 0.01

TABLE II. Internal conversion coefficients.

$E\gamma$ (kev)	K shell internal conversions electrons per disintegration[a]	K (experimental)	K (theoretical)[c] $E1$	$E2$	$M1$	$M2$
416	4.4×10^{-3}	1.3×10^{-2}	3.9×10^{-3}	1.3×10^{-2}	1.5×10^{-2}	5.3×10^{-2}
536	5.5×10^{-3}	5.5×10^{-3}	2.3×10^{-3}	6.5×10^{-3}	8.5×10^{-3}	2.6×10^{-2}
670	3.2×10^{-3}	3.2×10^{-3}	1.4×10^{-3}	3.6×10^{-3}	4.7×10^{-3}	1.4×10^{-2}
740	2.1×10^{-3}	2.4×10^{-3}	1.1×10^{-3}	2.8×10^{-3}	3.7×10^{-3}	1.1×10^{-2}
1150	(8.8×10^{-5})[b]	7×10^{-4}	4.7×10^{-4}	1.1×10^{-3}	1.4×10^{-3}	3.2×10^{-3}

[a] Data of Caird and Mitchell (reference 2).
[b] The number in parenthesis denotes that this is the total number of internal conversion electrons per disintegration.
[c] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICCK1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)], Part I. "Tables of Internal Conversion Coefficients" (privately circulated by M. E. Rose).

The theoretical conversion coefficients are so similar that it is not possible to make definitive transition assignments from the experimental results. However all multipoles higher than quadrupole can be ruled out from these data.

Gamma-gamma coincidence measurements were made with the axes of the two crystals at 90° to each other and the source 5.4 cm from each crystal. Lead shielding was positioned between the crystals to minimize spurious coincidences caused by gammas being Compton scattered from one crystal into the other. With the single channel window set on the 1150-kev gamma, the 670- and 536-kev gammas were found to be in coincidence. Using the 740-kev gamma as a gate pulse, the 416-, 670-, and 536-kev gammas were in coincidence (see Fig. 3).

The data for the angular correlations were taken every ten degrees between 90° and 180° or between 270° and 180°. The crystal used with the single channel analyzer, gate pulse, was the stationary detector. An equation of the form $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ was fitted by a least squares analysis on an IBM 704. These results were then corrected by a procedure due to Rose[7] for the finite angular resolution of the detectors. The standard deviations are defined by Eq. (30) of Rose's paper.

DISCUSSION

The spin and parity of the ground state of Xe^{130} is assumed to be (0+). The spin and parity of the first excited state at 536 kev has been established from Coulomb excitation of this level as (2+).[8] (Note: all gamma energies quoted are those determined in the present work.)

The experimental 670–536 kev angular correlation coefficients for the cascade de-exciting level C can be fitted with a $4(Q)2(Q)0$ or a $2(96\%\ D+4\%\ Q)2(Q)0$ sequence as is shown in Table III. See Fig. 4 for the latter. There is an anomaly, however, if the level C has either spin 2 or spin 4; positive parity is assumed. If the spin is 2 the 670-kev transition would have to be predominantly dipole, but in previous determinations of mixing ratios of similar transitions the radiations were predominantly quadrupole.[8] In the cases where the radiation is largely quadrupole the crossover from the upper (2+) level to the ground state was found to be quite weak.

If the spin of level C is 4, the log ft value, $\geqslant 9.8$, appears to be very large for a beta transition from a spin 5 state (I^{130} ground-state spin = 5) to a spin 4 state. A possible explanation based on the nuclear shell model for such a large log ft has been suggested by King.[9] In the region of $A=130$ both the neutrons and the protons are filling the orbitals between the closed shells at 50 and 82. In this region the $h_{11/2}$ orbital is populated by an odd number of nucleons as evidenced by the (2−) ground states of I^{124} and I^{126}. If in I^{130} the odd neutron

TABLE III. 670–536 kev correlation.

Sequence	A_2	A_4
Experimental	0.089 ± 0.011	-0.008 ± 0.017
$4(Q)2(Q)0$	0.102	0.0091
$2(96\%\ D+4\%\ Q)2(Q)0$	0.09	

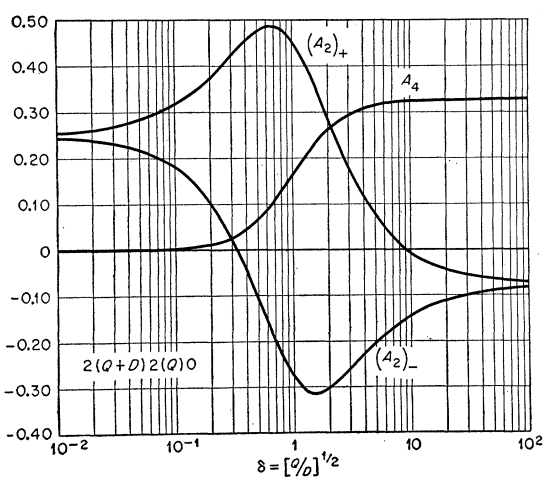

FIG. 4. Angular distribution coefficients as a function of dipole-quadrupole mixing for 2-2-0 sequence.

[7] M. E. Rose, Phys. Rev. **91**, 610 (1953).

[8] J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 108 (1953); Gertrude Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).

[9] R. W. King (private communication).

TABLE IV. 1150–670 kev correlation.

Sequence	A_2	A_4
Experimental	0.102±0.031	0.049±0.056
6(Q)4(Q)2	0.102	0.0091
5(D)4(Q)2	−0.072	
5(93%D+7%Q)4(Q)2	0.10	−0.005
5(12% D+88% Q)4(Q)2	0.10	−0.050

TABLE VI. 740–670 kev correlation.

Sequence	A_2	A_4
Experimental	0.088±0.017	−0.041±0.027
6(Q)4(Q)2	0.102	0.0091
5(94% D+6% Q)4(Q)2	0.09	−0.005
5(11% D+89% Q)4(Q)2	0.09	−0.051

is in the $h_{11/2}$ orbital and the odd proton is in one of the available positive parity orbitals, they could combine to give a (5−) ground state. The beta transition with the highest probability would be for the $h_{11/2}$ neutron to decay to a $g_{7/2}$ proton. This would be a once forbidden, unique, transition, $W_0=1770$ kev, and a log ft value of ~9 would be reasonable. All other possible transitions within this major shell would involve spin changes of 3 or greater. If the configuration mixing within the shell is such that the $h_{11/2}$ neutron and the $g_{7/2}$ proton orbitals have an overlap of 10% the log ft would be increased to $\gtrsim 10$.

If the spin of level C is 2, the 670–536 kev correlation leads to a value of $\delta_1=-(2.1\pm0.15)\times10^{-1}$ in the notation of Biedenharn and Rose[10] where the reduced matrix elements are defined with the j of the intermediate state on the right in the reduced matrix element. The double correlations 740–670 kev and 1150–670 kev and the 1–3 correlations 740–536 kev and 1150–536 kev have also been measured (see Tables IV, V, VI, and VII). If the spin assignment of 2 to level C is correct, the sign and magnitude of $\delta=(E2/M1)^{\frac{1}{2}}$ deduced from the double correlations, where the 670-kev transition is the second transition of the cascade, should be consistent with the result deduced from the 670–536 kev correlation. For the case of assignment 2+ to level C, only spin 4 for levels D and E would be compatible with the internal conversion data and the log ft values of the β^- groups to these levels. The double correlations 740–670 kev and 1150–670 kev can be fitted by $4(Q)2(D+Q)2$ with $\delta_2=0.2$. In a triple cascade with the intermediate radiation mixed it is not possible to define the δ so that the intermediate state j always occurs in the same position in the reduced matrix element[11] for the two double cascades, i.e., the mixed transition is the first transition in the 670–536 kev cascade and the same mixed transition is the second transition in the 1150–670 kev or 740–670 kev cascades. However, if the convention of reference 10 is followed, then $\delta_1=-\delta_2$. Thus, the results from the double correlations are consistent with regard to the magnitude and sign of δ for the mixed transition of the 670 kev.

For the 1–3 correlation with the intervening mixed radiation unobserved, the correlation function is

$$W(\theta)=W_{L_1}(\theta)+\delta^2 W_{L_1'}(\theta),$$

where δ^2 is the intensity ratio of the $2^{L_1'}$- to 2^{L_1}-pole.[12] There is no interference term because the mixed radiation is not observed. For the sequence $4(Q)2(D+Q)2(Q)0$ with $\delta^2=0.04$, $A_2=0.0482$ and $A_4=-0.0058$. The experimental coefficient A_2 for the 740–536 kev 1–3 correlation is 0.109±0.015. Since for all δ^2 of the $2\rightarrow2$ transition the coefficient A_2 is between 0.0510 and −0.0219 for the 1–3 correlation, the assignment of 2+ to level C is not consistent with the experimental result.

In view of these plausibility arguments, assignments of (4+) to level C of Xe^{130} and negative parity to the I^{130} ground state appear to be the most reasonable. These assignments are in agreement with Caird and Mitchell.

A linear polarization measurement of the 670-kev gamma ray would also permit a unique assignment for level C. However, such a measurement would be made complicated by the presence of higher energy gamma rays and by the rather short half-life of I^{130}.

Caird and Mitchell assigned spins and parities to levels D and E of Xe^{130} and the I^{130} ground state of (6+), (5−), and (6−), respectively. These assignments were based on log ft values and are self-consistent. The new I^{130} spin measurement, $I=5$, does not rule out the Xe^{130} assignments but angular correlation measurements were made on the gamma rays deexciting levels D and E in an attempt to obtain more information on these levels.

TABLE V. 1150-536 kev 1–3 correlation.

Sequence	A_2	A_4
Experimental	0.086±0.036	0.022±0.068
6(Q)4(Q)2(Q)0	0.102	0.0091
5(D)4(Q)2(Q)0	−0.114	
5(94% D+6% Q)4(Q)2(Q)0	0.086	−0.003
5(11% D+89% Q)4(Q)2(Q)0	0.086	−0.052

TABLE VII. 740–536 kev 1–3 correlation.

Sequence	A_2	A_4
Experimental	0.109±0.015	−0.029±0.021
6(Q)4(Q)2(Q)0	0.102	0.0091
5(92% D+8% Q)4(Q)2(Q)0	0.11	−0.004
5(13% D+87% Q)4(Q)2(Q)0	0.11	−0.050

[10] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

[11] M. E. Rose, Oak Ridge National Laboratory Report ORNL-2516, 1958 (unpublished).

[12] M. E. Rose, Oak Ridge National Laboratory Report ORNL-155, 1953 (unpublished). D. H. Wilkinson (unpublished).

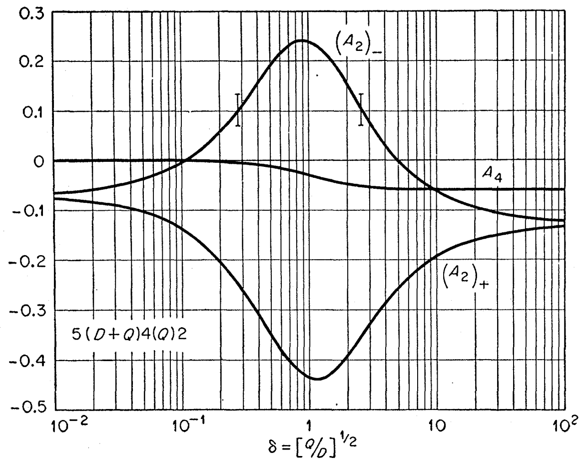

FIG. 5. Angular distribution coefficients as a function of dipole-quadrupole mixing for 5-4-2 sequence.

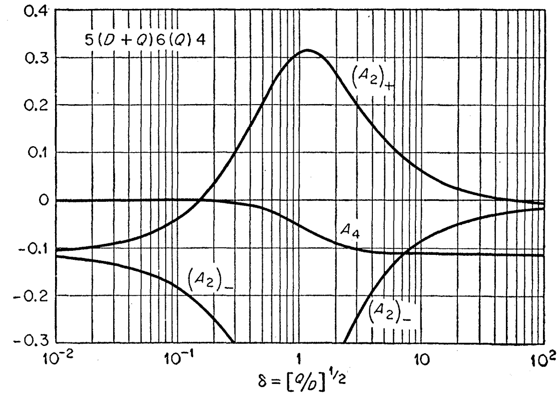

FIG. 7. Angular distribution coefficients as a function of dipole-quadrupole mixing for 5-6-4 sequence.

The log ft of the beta transition to level E is 5.7. This is in the range of allowed ft values. An allowed transition would require that the parity of level E be the same as that of the I^{130} ground state; negative, according to the present arguments. The beta decay to level E is more than 10^4 times faster than the decay to level C; the latter has tentatively been given a (4+) assignment. The simplest explanation for this large difference in decay rates is that level E has a spin >4. Of course level E could have the same spin as level C and still be populated by a relatively faster beta decay if there were no retardation factors present in the decay to level E. From their measurement of the internal conversion coefficient Caird and Mitchell assigned the 1150-kev transition an $E1$ multipolarity. These factors are in agreement with level E being (5−).

The present results for the 1150–670 kev and the 1150–536 kev angular correlations rule out the possibility of the 1150-kev transition being pure dipole. However, the 1150–670 kev correlation can be fitted with a 5(93% D+7% Q)4(Q)2 or a 5(12% D+88% Q)4(Q)2 sequence (see Fig. 5). The 1150–536 kev 1–3 correlation can be fitted with the same dipole-quadrupole mixtures for the 1150-kev gamma ray (see Fig. 6). The assignment of 6− to level E requires a pure $M2$ transition for the 1150-kev transition; this assignment can be eliminated by a comparison of the observed K shell conversion coefficient with the theoretically expected value for $M2$. A pure $E2$ transition is in agreement with the observed angular correlation and the observed K shell conversion coefficient so that 6+ is a possible assignment. The transition from level E to level C probably involves a change of parity and therefore the 5− assignment requiring a 93% $E1$+7% $M2$ mixture seems a more likely assignment than 6+ or 5+.

The log ft of the beta group populating level D is 6.5. This is in the range of ft value for once forbidden, nonunique, beta decays. Such a transition involves a change of parity and this would require the parity of level D to be positive, since the present work indicates that the parity of I^{130} is negative.

The same argument that was advanced in the preceding section to suggest that the spin of level E is >4 can be used in the present case to suggest that the spin at level D is also >4. Namely, that the ratio of the decay rates to levels D and C, $>10^3$, can be explained most simply by level D having a larger spin than level C.

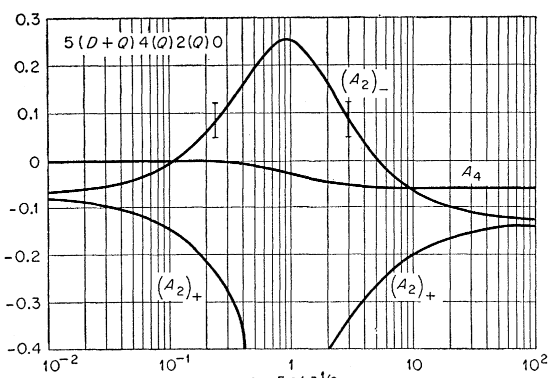

FIG. 6. Angular distribution coefficients as a function of dipole-quadrupole mixing for 5-4-2-0, 1-3 correlation.

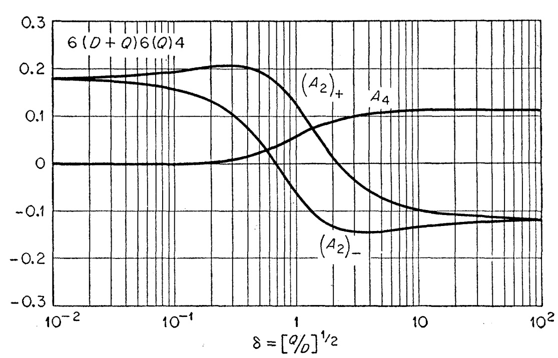

FIG. 8. Angular distribution coefficients as a function of dipole-quadrupole mixing for 6-6-4 sequence.

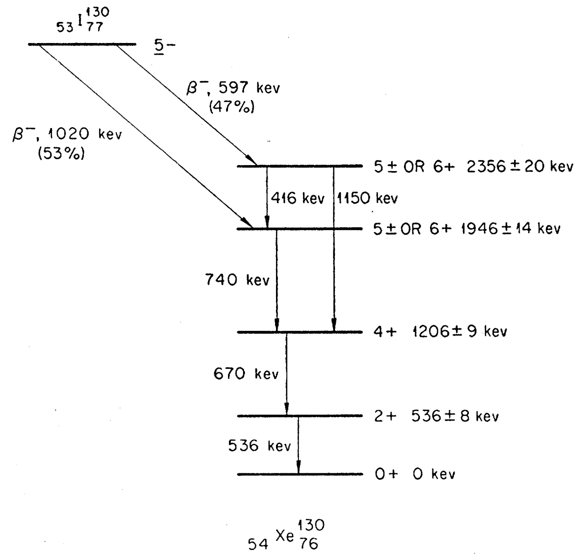

FIG. 9. Level scheme deduced from present study and directly measured spin of I^{130}. Beta transition energies were obtained from Caird and Mitchell.[2]

The experimental and theoretical coefficient for the 740–670 kev and the 740–536 kev correlation are nearly identical to the 1150–670 kev and 1150–536 kev coefficients. Therefore the spin of level D can be specified only to the same extent as was that of level E, 5 or 6. Once again, the assignment of 6− to level D can be eliminated because the observed K-shell internal conversion coefficient is quite different from that expected theoretically for a pure $M2$ transition.

The experimental coefficients obtained for the 416–740 kev correlation are: $A_2=0.179\pm0.026$ and $A_4=0.040\pm0.037$. These results can be fitted with the following sequences: $5(D+Q)6(Q)4$, $6(D+Q)6(Q)4$, $6(D+Q)5(D+Q)4$, or $5(D+Q)5(D+Q)4$ (see Fig. 7 and 8 for the first two cases). A $6(Q)4(Q)2$ sequence, $A_2=0.102$ and $A_4=0.0091$, appears to be very unlikely.

The coefficients obtained for the 416–670 kev 1–3 correlation are: $A_2=0.162\pm0.017$ and $A_4=-0.069\pm0.030$. These can be fitted with a $6(D)6(Q)4(Q)2$ sequence; $A_2=0.178$. The experimental results could undoubtedly be fitted to other combinations of spins 5 and 6 for levels D and E and mixtures for the 416-kev transition.

Therefore the results of the 416–740 kev and the 416–670 kev correlations are not very helpful in trying to choose between spins 5 and 6 for levels D and E.

CONCLUSIONS

The results of the present study are summarized in the level scheme shown in Fig. 9. Adopting the plausible explanation of the anomalously large log ft, $\geqslant 9.8$, of the unobserved 1770-kev transition to level C, the spin and parity of the latter level are tentatively given as (4+). The spins and parities of levels D and E can only be suggested to be (5±, 6+) and (5±, 6+), respectively.

ACKNOWLEDGMENTS

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