assignments for the ^{132}Xe and ^{132}Ba levels in Fig. 7 are those from the angular correlation measurements of Robinson *et al.*,[2] and the ground-state spin for ^{132}Cs is the measured value of Nierenberg *et al.*[17] There are two numbers on each electron capture or positron branch. One gives the relative intensity and the other in brackets gives the log*ft*. These log*ft* values support a negative parity assignment for ^{132}Cs.

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Nuclear Energy States of I^{129}†

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The quantum radiations emitted in the decay of Te^{129m}-Te^{129} have been investigated with application of a Ge(Li) detector, scintillation counters, coincidence techniques, and multichannel analysis. In addition to the well-known 27-keV gamma ray, twenty-three others have been detected at energies of 205, 250, 273, 277, 340, 448, 455, 482, 523, 548, 550, 630, 660, 698, 725, 770, 797, 810, 835, 945, 1085, 1112, and 1222 keV. Thus, six pairs of gamma rays are present which exhibit within each pair an energy difference of 27 keV. Excited states in I^{129} are established at 27, 277, 482, 550, 725, 797, and 1112 keV by this energy difference. Additional excited states are found at 837, 1065, 1222, and 1385 keV by coincidence experiments.

I. INTRODUCTION

THE nuclear energy levels of I^{129} have been investigated experimentally[1–10] through the β^- decay of Te^{129m}(33 day) and Te^{129}(70 min), and theoretically.[11,12] The earlier experiments[1–4] culminated in a level scheme proposed by Graves and Mitchell[4] who reported that Te^{129m} decays by de-excitation of the 106-keV isomeric state and by β^- decay to excited states in I^{129}, the β^- emission occurring in 5% of the transitions. More recent studies[6] have indicated β^- emission in 32% of the disintegrations. This result was suggestive of the need for further investigation of the β^- decay of Te^{129m}, and in the course of such measurements,[5,7–10] many previously undetected gamma rays were discovered. The various nuclear-structure diagrams of I^{129} resulting from some of the researches cited above[4,5,7,8,10] are depicted in Fig. 1.

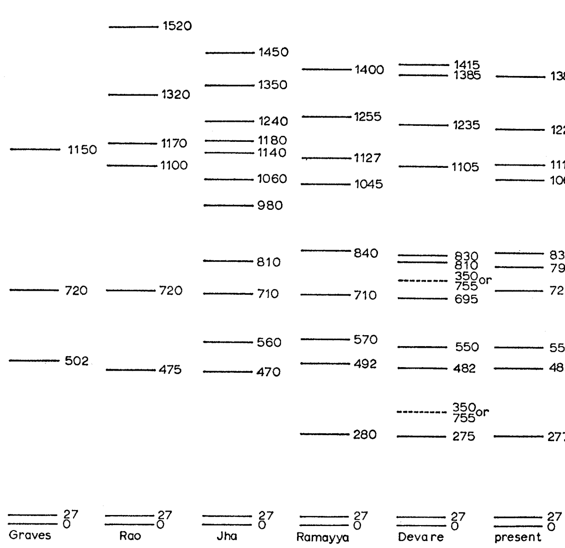

FIG. 1. Energy states of the nucleus of I^{129} as reported in previous studies. The structure indicated by the present results is also given. Energies are in keV.

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Development of solid-state gamma-ray detectors[13] has made it possible to resolve gamma rays separated by as little as 10 keV in energy. The aims of the present investigation have been to search for gamma rays too closely spaced in energy to be resolved by previously employed NaI(Tl) scintillation spectrometers and to obtain data concerning the level structure of I^{129} to be compared with theory.[11,12] Singles spectra arising from unconverted quanta were observed in a lithium-diffused germanium detector of two-millimeters depletion-layer thickness operating with 50-V reverse bias at liquid-nitrogen temperature. The resolution, largely due to the electronic limitations, was 5.5 keV full width at half-maximum (FWHM).

II. EXPERIMENTAL PROCEDURES

One hundred milligrams of metallic tellurium, isotopically concentrated in Te^{128} to an extent of 91.8%, were irradiated for seven days in the Oak Ridge Research Reactor, producing an activity of about 250 μCi. After a time of 21 days, chemical separations were performed to remove I^{131} grown from Te^{131m}(1.2 day) and Te^{131}(25 min) formed when neutrons were captured by residual amounts of Te^{130}, with a concentration 6% in the target material.

A lithium-drifted germanium detector was used to give singles spectra in which most of the gamma rays were clearly resolved. To reconstruct an energy-level diagram from these gamma-ray energies, gamma-gamma coincidence data were obtained by using two sodium-iodide scintillation counters, each with a diameter of 10 cm and a thickness of 7.5 cm. The signals from the counters were fed to a slow-fast coincidence circuit, the fast portion operating in crossover mode. The pulses of the display counter were recorded upon a TMC-400 multichannel analyzer, gated by the coincidence signal.

III. MEASUREMENTS: THE SPECTRUM OF SINGLE COUNTS

Taking time zero arbitrarily to be that of the first observed spectrum, the complete gamma-ray spectrum of Te^{129m}-Te^{129} was observed at times zero, 3 days, 32 days, and 128 days in the lithium-drifted germanium detector. A typically observed spectrum is shown in Fig. 2, where photopeaks are to be noted at quantum

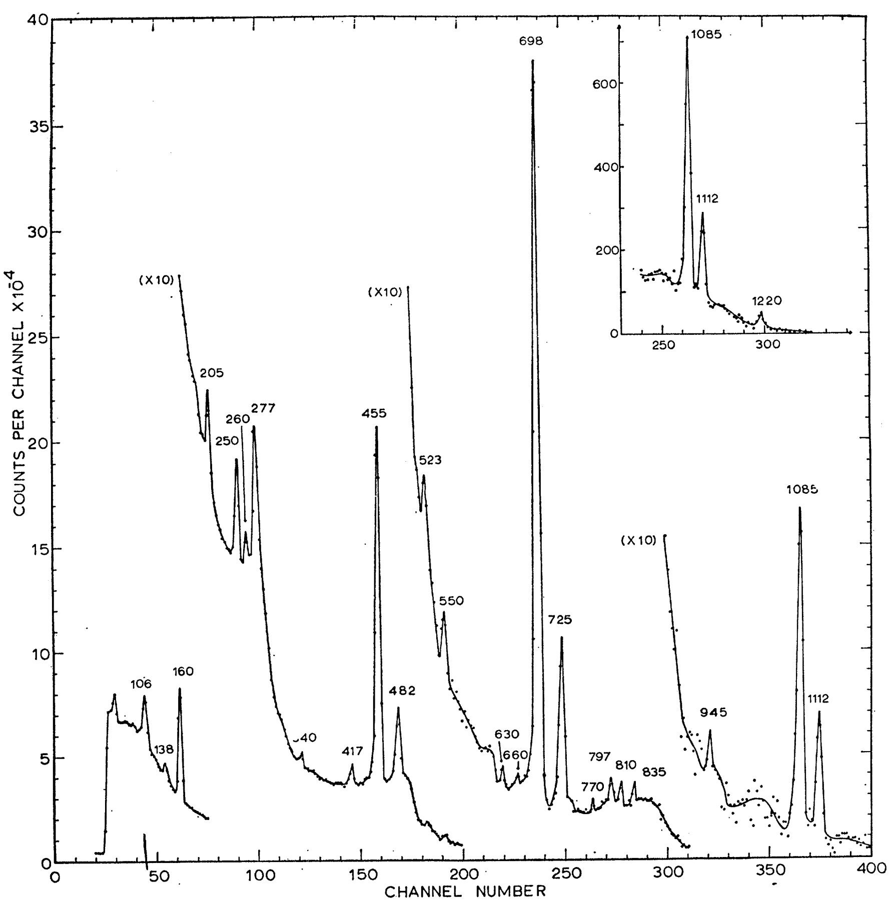

FIG. 2. Spectrum of gamma rays emitted in decay of Te^{129m}-Te^{129} as observed in a Ge(Li) detector. The 27-keV radiation is not shown. Energies are in keV.

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energies indicated. The data obtained from results of Fig. 2 are summarized in Table I. The percent of disintegrations in which each gamma ray is emitted is also given based upon the assumption that internal conversion is negligible in all cases. The computation of the percentage of transitions in which each gamma ray is emitted also required the assumption that the 482-keV level of I^{129} is primarily fed by a beta spectrum having an intensity of 10.2%[8] as compared to the extremely small contribution for the 630-keV gamma ray, emitted in competition with the 1085- and 1112-keV quanta from the 1112-keV level populated in only a fraction of a percent[8] of the disintegrations (see disintegration scheme of Fig. 5). This calculation of the percent of transitions in which each quantum is emitted also required correction of the area under each photopeak for variation of absorption in the germanium detector with quantum energy, and for variation with energy of the ratio of total absorption coefficient to full-energy absorption coefficient. As the depletion layer is only 2 mm thick, the full energy-absorption coefficient was assumed to be equal to the photoelectric-absorption coefficient. Finally corrections were also applied for the absorption of the detected radiations in all materials intervening between the source and detector, including the steel case of the detector, to obtain the over-all efficiency versus energy characteristic curve of the detector.

Experimental verification of this curve was obtained by measuring with the germanium detector the relative intensities of gamma rays emitted from Br^{82}, with energies in approximately the same region as those being studied. After these relative intensities were corrected according to the calculated efficiency versus energy curve, the results agreed within a few percent with the corresponding relative intensities obtained from scintillation counter experiments.

The gamma rays having photopeaks at 138 and 417 keV are assigned to the presence of Te^{127m}(105 day), produced by slow-neutron capture in Te^{126}, which had an isotopic concentration of 2.2% in the target material. The photopeak corresponding to a quantum energy of 160 keV does not decay with the half-life of Te^{129m}. It appears to be emitted in the decay of Te^{123m}(104 day). Te^{122} was present in the target with an abundance of less than 0.1%. Te^{123m} might also have been formed by inelastic neutron scattering, because Te^{123} also was present with an abundance of less than 0.1%. The origins of the 260-keV gamma ray are unknown. All the remaining photopeaks of Fig. 2 are assigned to the decay of Te^{129m}.

The presence of a 27-keV $M1$ transition between the ground state and first excited state of I^{129} has been well established in earlier experiments.[4,5,7,8,10]

Owing to the high resolution of the Ge(Li) detector, it was possible to resolve six pairs of gamma rays, each pair showing an energy difference of 27 keV. This recurring energy separation exhibited within each pair of quanta is interpreted in each case as indicating two transitions commencing at the same nuclear state, one terminating at the first excited state at 27 keV, the other at the ground state. Thus was established excited states at 277, 482, 550, 725, 797, and 1112 keV in I^{129}.

TABLE I. Energies and relative intensities of the gamma rays emitted in the decay of Te^{129m}–Te^{129} as indicated by the data of Fig. 2.

Quantum energy (keV)	Relative intensity	Emission in percent of disintegrations
205	1.53	0.12
250	0.48	0.04
277[a]	12.10	1.00
340	0.74	0.06
455[b]	100.00	8.25
482	22.20	1.83
523	2.65	0.22
550[c]	2.61	0.21
630	1.01	0.08
660	0.60	0.05
698	83.60	6.90
725	19.80	1.63
770	3.53	0.29
797	2.72	0.22
810	1.53	0.13
835	1.44	0.12
945	0.62	0.05
1085	9.86	0.82
1112	3.03	0.25
1222	0.60	0.05

[a] Composite photopeak containing contributions from 273- and 277-keV gamma rays.
[b] Composite photopeak containing contributions from 448- and 455-keV gamma rays.
[c] Composite photopeak containing contributions from 548- and 550-keV gamma rays.

IV. MEASUREMENTS: GAMMA–GAMMA COINCIDENCE DATA

The gamma-gamma coincidences were measured in the two thick crystals of NaI(Tl) described earlier. The angular separation of the axes of the counters was $\pi/4$ rad, and the counters were adequately shielded from each other to prevent occurrence of coincidences because of scattering effects. The resolving time of the coincidence circuit was 4.8×10^{-7} sec. Data were accumulated by observing the total coincidence spectra (genuine plus chance), and the chance spectra simultaneously in the two halves of the memory of the TMC-400 multichannel analyzer. In a first sequence of measurements, the "gate" pulse of the slow-fast coincidence circuit was moved continuously from 140 to 455 keV with widths varying from 20 to 35 keV. In all, nine coincidence spectra were obtained, five representative ones being displayed in Fig. 3. Subsequently, the gain of the amplifier associated with the display detector of the coincidence circuit was reduced, and the gate was moved continuously from 505 to 1180 keV in thirteen steps, the width of the gate varying from 35 to 110 keV. Five of the thirteen coincidence spectra so obtained are shown in Fig. 4. As the position in energy of the gating interval was altered in continuous fashion to obtain the curves of Figs. 3 and 4 and the many other curves not shown, the full-energy peaks of gamma rays detected by the display detector of the coincidence system were observed to increase in intensity whenever a full-energy peak or peaks due to the gamma rays in the same cascade were included in the gate width. Neighboring gating intervals often showed a similar spectrum of coincidences, arising from the presence in the gate of Compton distributions of high-energy gamma rays, but when the gate was moved to include a full-energy peak or peaks, certain full-energy peaks of the display detector spectrum became enhanced to indicate the advent of genuine cascades. The results obtained from consideration of the gamma-gamma coincidence data of Figs. 3 and 4 are summarized in Table II. As previously remarked, additional coincidence spectra not shown made supplemental contribution in interpreting the specific curves presented in Figs. 3 and 4. For example, the spectrum of curve *F*, Fig. 4 was obtained for the gating interval (810–850) keV where full energy peaks at 250, 273, 277, and 550 keV are seen to be coincident with pulses lying on the interval cited. Data not shown were collected for the gating interval (755–800) keV in which the intensities of the 250-, 273-, 277-, and 550-keV peaks decreased, and peaks at 340 and 660 keV put in appearance. When the gate position was finally reduced to (705–750) keV,

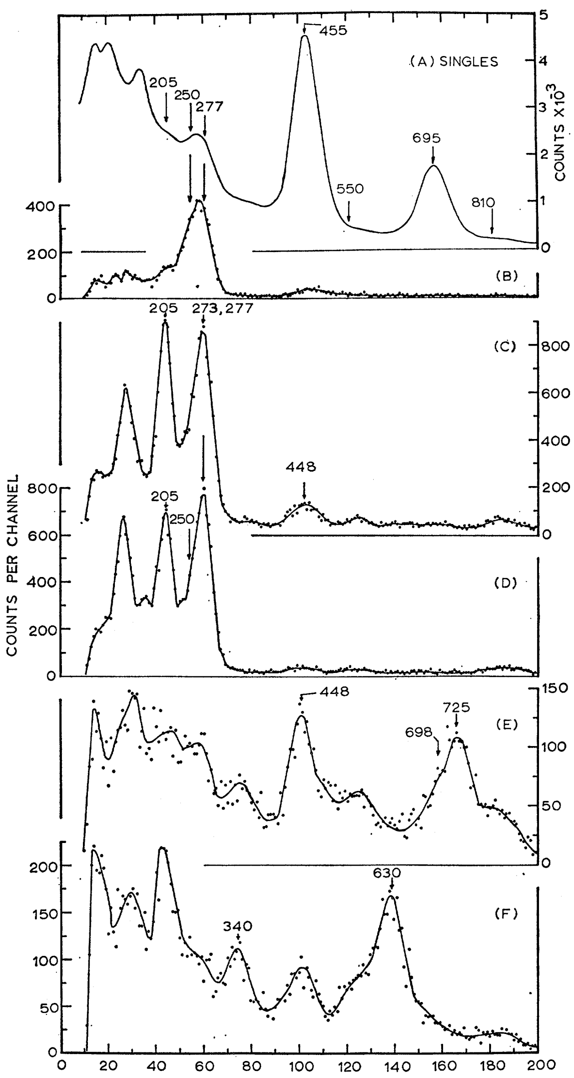

FIG. 3. Spectra of coincident gamma rays detected in the display tube of a slow-fast coincidence circuit. The gating intervals are as follows: curve B, 200–225 keV; curve C, 225–250 keV; curve D, 250–285 keV; curve E, 325–360 keV; curve F, 435–455 keV. Additional data concerning these coincidence experiments are presented in Table II.

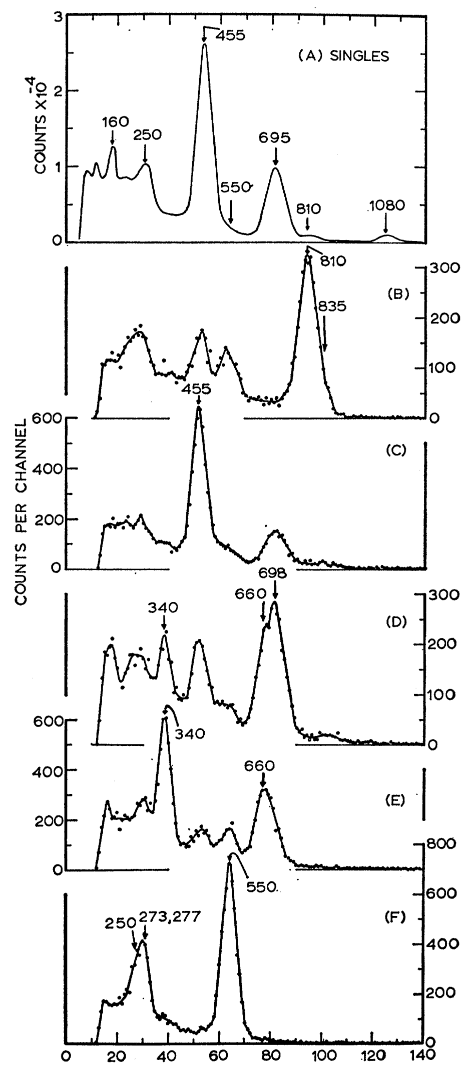

FIG. 4. Extension of spectra presented in Fig. 3. The gating intervals are as follows: curve B, 545–590 keV; curve C, 610–645 keV; curve D, 655–700 keV; curve E, 705–750 keV; curve F, 810–850 keV. Additional data concerning these coincidence experiments are presented in Table II.

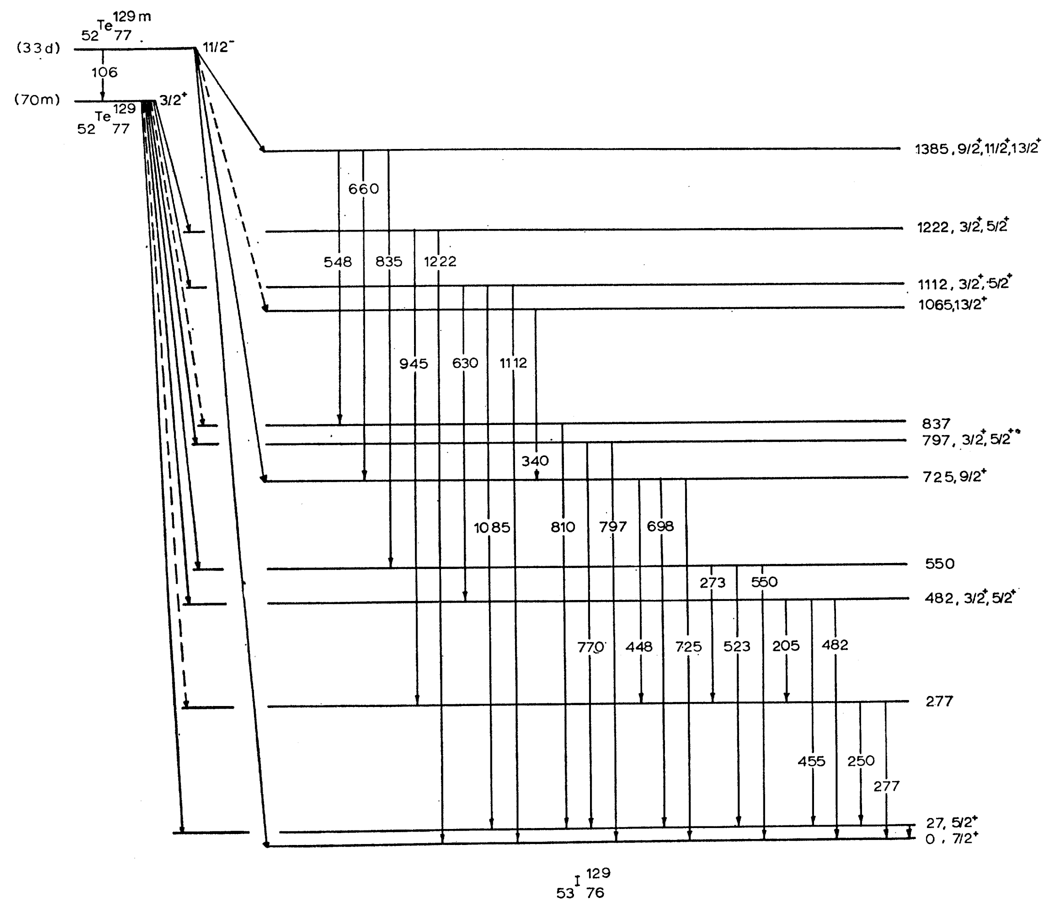

FIG. 5. Disintegration scheme of Te^{129m}–Te^{129} showing level structure of I^{129}. Certain features of the scheme are drawn from the work of others referred to in the text. Energies are in keV.

the 340- and 660-keV peaks became predominant, the other peaks still being present but greatly reduced. This last measurement showed the 725-keV gamma ray to be coincident with the quanta at 340 and 660 keV. The data of curve *D*, Fig. 4 were taken with the gate at (655–700) keV, showing the 698-keV gamma ray to be coincident with the 660- and 698-keV quanta. Thus, the interpretation can be extended from curve to curve, commencing with the gate interval of highest energies.

TABLE II. Results of the gamma-gamma coincidence experiments. Gamma rays prominently coincident with the various selected energy intervals.

Energy interval (keV)	Quanta coincident with pulse in gating interval (keV)
Fig. 3, curve *B*, (200–225)	250, 277
Fig. 3, curve *C*, (225–250)	205, 273, 277, 448
Fig. 3, curve *D*, (250–285)	205, 250, 273, 277
Fig. 3, curve *E*, (325–360)	448, 698, 725
Fig. 3, curve *F*, (435–455)	340, 630
Fig. 4, curve *B*, (545–590)	810, 835
Fig. 4, curve *C*, (610–645)	455
Fig. 4, curve *D*, (655–700)	340, 660, 698
Fig. 4, curve *E*, (705–750)	340, 660
Fig. 4, curve *F*, (810–850)	250, 273, 277, 550
Data not shown (900–960)	250, 277

The data of the spectrum of Fig. 2 and the coincidence data of Table II, combined with certain measurements of others,[8,10] yield the disintegration scheme of Fig. 5. Possible spin values of some of the nuclear states of I^{129} have been determined by calculating $\log ft$ for some of the beta spectra. The absolute intensities, in percent of disintegrations, of the beta-ray spectra were obtained

TABLE III. Values of $\log ft$ and other properties for certain of the beta transitions of Te^{129m}–Te^{129}.

Initial nucleus	Final energy state in I^{129} (keV)	E_β(max) (keV)	Intensity in percent of disintegrations	$\log ft$	Classifications
Te^{129}	1222	267	0.10	5.1	Allowed
Te^{129}	1112	377	1.15	5.5	Allowed
Te^{129m}	1065	530	0.06	10.1	First-forbidden
Te^{129}	797	692	0.51	6.8	Allowed
Te^{129m}	725	870	8.53	8.8	First-forbidden
Te^{129}	482	1007	10.20	6.1	Allowed

from the percent intensities of the gamma rays de-exciting the levels fed by the respective beta-ray spectra. These values of $\log ft$ are summarized in Table III. The initial nucleus of each beta spectrum of Table III is taken to be that indicated by earlier investigations.[8,10]

V. DISCUSSION OF RESULTS

The shell-model orbitals of Te^{129m} and Te^{129} are $h_{11/2}$ and $d_{3/2}$, the 106-keV transition[4] being $M4$. The ground state of I^{129} has a measured spin[14] of $\frac{7}{2}$, shell-model orbital $g_{7/2}$. By lifetime measurements[15] and study[10] of the $(L+M)$-shells conversion coefficient, the 27-keV transition has been shown to be $M1$, the spin and parity of the 27-keV state in I^{129} being $\frac{5}{2}+$, shell-model orbital $d_{5/2}$. If indeed the allowed transitions of Table III do stem from Te^{129}, the possible spins and parities of the 482-, 797-, 1112-, and 1222-keV levels would be $\frac{3}{2}+$ or $\frac{5}{2}+$. The spin and parity of the 725-keV level, fed by a first-forbidden spectrum initiating at Te^{129m}, could be $\frac{7}{2}+$ or $\frac{9}{2}+$. The 1065-keV level does not de-excite with a transition to either the ground state or the 27-keV state. Its spin is therefore assumed to be $13/2+$, making the spin of the 725-keV state more probably $\frac{9}{2}+$. These various possible assignments of spin and parity would suggest that the bulk of the observed gamma-ray transitions in I^{129} are $M1$ or $E2$ or a mixture thereof. Others[10] have suggested possible spins and parities of $\frac{9}{2}+$, $11/2+$, or $13/2+$ for the 1385-keV level. All of these possible values are consistent with the gamma transitions from that level as shown in the decay scheme of Fig. 5.

Some theoretical efforts have been made to compute the energies of the excited states of I^{129}. Banerjee and Gupta[11] have based their theoretical calculation upon a model which assumes the nucleus to be an even-even core, with its spectrum of vibrational levels, and an odd nucleon giving rise to single-particle states. They find thirty-three excited states between the ground state and an excitation energy of 1075 keV. Somewhat better agreement has been found with the calculations of Kisslinger and Sorensen,[12] which are based upon the assumption of spherical nuclear shape with residual forces. They report the possibility of ten excited states on approximately the same energy interval. The spins predicted are such that virtually all the levels of either theoretical calculation should have been excited in the decay of Te^{129m}–Te^{129}. It is concluded that the proposed decay scheme produces best qualitative agreement with the works of Kisslinger and Sorensen.[12]

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Nuclear Structure and Parity Impurities*

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Nuclear-structure calculations, relevant to the evaluation of irregular gamma-ray transition amplitudes (parity-forbidden multipoles), have been performed. General expressions have been derived for the case of one-particle states in odd-A nuclei with spherical or spheroidal shape. In particular, the pseudoscalar operator $\boldsymbol{\sigma}\cdot\mathbf{p}$ is discussed. The case of regular $M1$ plus irregular $E1$ transition is considered as an application. Results are derived for the transitions of 482 keV in Ta^{181}, 343 keV in Lu^{175}, and 14 keV in Fe^{57}. For Ta^{181}, it is possible to calculate the magnitude and the sign of the nuclear matrix-element ratio R. Comparing the theoretical result for the circular polarization, $P\propto FR$, with recent measurement, gives the following limits for the amplitude factor F: $9\lesssim 10^7\times F\lesssim 110$. This result agrees in sign and order of magnitude with estimates derived from the current-current theory of weak interactions.

I. INTRODUCTION

RECENTLY, experimental proof has been obtained for the existence of parity admixtures in nuclear states.[1,2] Such impurities are predicted by theories of weak interactions. The current-current hypothesis[3] implies a weak nucleon-nucleon force, with the same parity-violating properties as the interaction responsible for beta decay. From this theory a form of the weak

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