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Radioactive decay of 9.2-min $^{130}I^m$ to levels of ^{130}Xe

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The γ-ray transitions following the decay of 9.2-min $^{130}I^m$ have been measured using Ge(Li) Compton-suppressed γ-ray spectrometry. Three new levels in ^{130}Xe have been proposed at 2762.6, 2644.9, and 2307.8 keV and new β branches observed to four levels at 1632.6, 2385.5, 2544.4, and 2637.5 keV. The results are compared with those of other recent studies and the difficulties of finding an adequate theoretical description discussed.

[RADIOACTIVITY $^{130}I^m$ from $^{129}I(n,\gamma)$. Measured E_γ, I_γ. ^{130}Xe, deduced levels, E_β, I_β, J, π. Enriched target. Ge(Li) detector.]

I. INTRODUCTION

The properties of the levels of ^{130}Xe have been the subject of a number of recent experimental investigations. These[1,2] include Te($^{3,4}He, xn\gamma$) studies, $^{129}Xe(n,\gamma)$ studies,[3] investigation[4] of the radioactive decay of 1^+ 30-min ^{130}Cs, and the study of the decay[4,5] of the 9.2-min and 12.4-h isomers of ^{130}I. As the ^{130}Xe nucleus is a transitional nucleus and poorly or incompletely described by most conventional theoretical approaches, considerable importance is attached to a precise determination of its properties. The results of the two recent studies[4,5] of the decay of ^{130}I isomers stand in considerable disagreement. Owing to the more sensitive instruments employed by Hopke *et al.*[4] in the study of the 12.4-h ^{130}I, the differences between the results reported by Bakiev *et al.*[5] and Hopke *et al.*[4] can be reconciled. We are reporting in this paper the results of a careful further investigation of the decay of 9.2-min $^{130}I^m$.

II. EXPERIMENTAL PROCEDURES

In order to identify and confirm as many γ rays from $^{130}I^m$ decay as possible, four Ge(Li) γ-ray detectors were used: a 7-cm^3 Compton-suppressed system (CSS), a 19-cm^3 high-resolution detector, a 0.7-cm^3 low-energy detector, and a 40-cm^3 detector with only modest resolution. The sources were prepared by irradiating enriched ^{129}I as PbI_2 in the Livermore pool-type reactor for up to 1 min at a flux of $1.5\times10^{13} n\ cm^{-2}\ sec^{-1}$. Packaging and transfer of the samples to the counting room required a period of $\approx$3 min. In order to minimize the interference from 12.4-h $^{130}I^g$, each sample was counted for only 10 min on each of the detectors in the sequence in which they are listed above. As $^{130}I^g$ emits no γ rays with energies above 1700 keV,[4] the spectra from the 19-cm^3 detector were utilized to search for γ rays between 1500 and 3000 keV. A Pb-Cd absorber was used to reduce the intensity of the lower-energy γ rays and permit placement of the sample close to the detector to obtain high counting efficiency for the higher-energy γ rays. The spectra from the two large detectors were used to determine the half-lives of the higher-energy γ rays. The precise energy values listed in Table I were determined in a second series of irradiations in which a number of samples were counted on the 19-cm^3 detector for 15 min each along with a group of well-known γ-ray standards.

The relative intensities are normalized to a value of 1000 for the 536.1-keV γ ray. The intensities for those γ rays fed by both isomers were determined by subtracting the contributions from $^{130}I^g$ from the gross intensities by using the 739.5-keV γ ray of $^{130}I^g$ decay for normalization. The 739.5-keV γ ray arises from the decay of the 6^+ state at 1944.1 keV and is assumed to have no feeding from 2^+ $^{130}I^m$ decay. For some of the weaker γ rays, the resulting values are accompanied by large uncertainty values.

III. DECAY SCHEME OF $^{130}I^m$

Our proposed decay scheme for 9.2-min $^{130}I^m$ incorporating 33 γ rays is shown in Fig. 1. New levels are proposed at 2307.8 and 2762.6 keV on the basis of γ rays at these energies and a new level is proposed at 2644.9 keV on the basis of three deexcitation γ rays. We observe β feeding to levels at 2544.4 and 2637.2 keV which may possibly be associated with levels previously reported in neutron-capture-γ-ray work.[3] New β branches have been observed to levels at 1632.6 and 2385.5 keV whose identity had been established in earlier decay studies.[4-6] Of the three levels at 2223, 2243, and 2296 keV to which β branching was proposed by Bakiev *et al.*[5] but not by Hopke *et al.*,[4] we observed only the population of the 2296-keV level.

The 2223- and 2243-keV levels decay by emission of 1687- and 1707-keV γ rays, respectively. These two γ rays reported by Bakiev *et al.*[5] in the decay of $^{130}I^m$ were observed by Fessler, Julian, and Jha[6] as well as by Hopke *et al.*[4] in the decay of 1^+ ^{130}Cs but were not observed in the present work. We present in Fig. 2 an expanded plot of the CSS spectrum of the region from 1600 to 1800 keV showing for comparison the 1614.10- and 1759.97-keV γ rays.

TABLE I. Energies and intensities of $^{130}I^m$ γ rays.

E_γ (keV) [a]	I_γ (536 = 1000) [a]	From/To
352.27 (20)	0.07 (2)	2494/2150
427.93 (04)	0.022 (6)	1632/1204
510.35 (02)	0.23 (3)	1632/1204
536.09 (02)	1000	536/ 0
586.05 (02)	68.1 (7)	1122/ 536
603.53 (44)	0.013 (1)	1808/1204
668.54 (02)	0.69 (4)	1204/ 536
685.99 (02)	0.022 (1)	1808/1122
837.03 (25)	0.051 (2)	2644/1808
946. (0.5)	0.05 (2)	2150/1204
1028.11 (04)	2.49 (6)	2150/1122
1096.48 (06)	0.16 (2)	1632/ 536
1122.15 (05)	10.7 (2)	1122/ 0
1174.22 (25)	0.081 (20)	2296/1122
1263.53 (32)	0.13 (3)	2385/1122
1272.12 (04)	0.016 (1)	1808/ 536
1380.15 (04)	2.29 (6)	2502/1122
1440.18 (08)	0.68 (4)	2644/1204
1614.10 (04)	28.5 (5)	2150/ 536
1759.97 (05)	1.88 (20)	2296/ 536
1849.30 (30)	0.11 (2)	2385/ 536
1958.02 (04)	1.18 (6)	2494/ 536
1966.04 (04)	3.32 (17)	2502/ 536
1989.10 (20)	0.15 (4)	
2008.35 (08)	0.287 (30)	2544/ 536
2029.30 (40)	0.027 (12)	
2092.29 (10)	0.32 (3)	2628/ 539
2101.42 (05)	0.63 (4)	2637/ 536
2108.80 (05)	0.65 (4)	2644/ 536
2150.15 (05)	1.33 (6)	2150/ 0
2296.21 (12)	0.24 (2)	2296/ 0
2307.76 (18)	0.14 (2)	2307/ 0
2502.20 (05)	0.84 (4)	2502/ 0
2544.03 (60)	0.033 (10)	2544/ 0
2762.60 (30)	0.056 (8)	2762/ 0

[a] The numbers in parentheses represent the uncertainty in the last digit (s) of the value by which they stand.

Two low-intensity γ rays were observed at 1989.1 and 2029.3 keV that were not placed in the decay scheme. The extremely low intensity of the 2029.3-keV γ ray and the proximity of the 1989.1-keV γ ray to the single-escape peak of the 2502.20-keV γ ray made their clear identification as $^{130}I^m$ rays impossible. The weak 946-keV γ ray is also somewhat uncertain as it is a part of a peak including the 944.21-keV γ ray from $^{130}I^g$ decay.

During the preparation of this article, the results of a study by Gelletly, Kane, and Mackenzie of the $^{129}Xe(\text{res } n, \gamma)^{130}Xe$ reaction became known to us, as did our results to them. They[7] also observed γ rays at 2092, 2028.8, and 2101 keV as well as a γ ray at 1987.6 ± 0.7 keV. The former γ rays are believed to be the same as three we observe at those energies while the 1987.6-keV γ ray is not thought to be the same as our 1989.1 ± 0.2 keV. They also observed strong capture to and deexcitation from the level at 2762 keV. They observed a low-spin level at 2632.4 ± 1.7 keV that deexcites by a different pattern than the level we propose at 2637.1 keV. Our level placement is somewhat dependent upon the level at 2635 ± 2 keV observed by Groshev *et al.*[3] As the 2635 ± 2-keV

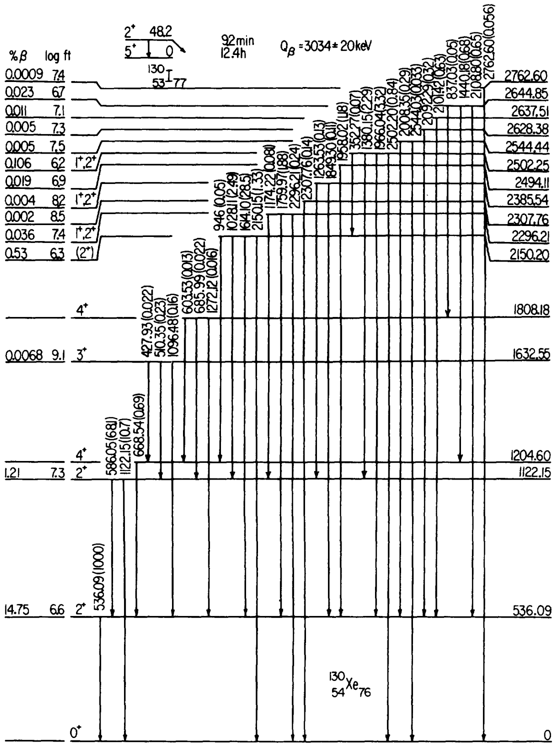

FIG. 1. Decay scheme for 9.2-min $^{130}I^m$.

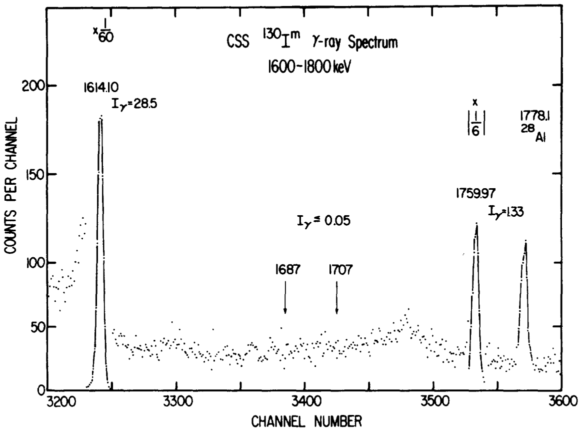

FIG. 2. Expansion of the region of the CSS spectrum between 1600 and 1800 keV. An upper limit for intensity of possible 1687- and 1707-keV γ rays is shown $[I(536\gamma)=1000]$.

level of Groshev *et al.*[3] is most likely to be identified with the 2632.4 ± 1.7-keV level of Gelletly *et al.*,[7] then the basis for our placement of the 2101.4-keV γ ray as deexciting a 2637.5-keV level is weakened.

Three γ rays are placed in our decay scheme on the basis of empirical arguments, the abovementioned 2101.4-keV γ ray, the 2092.3-keV γ ray from the 2628.4-keV level, and the 2307.8-keV γ ray from the 2307.8-keV level. Owing to the restrictions of Q_β the 2092.3- and 2101.4-keV γ rays can only feed the 536.1-keV γ ray as shown in Fig. 1 or feed the ground state. However, with the exception of the 2762-keV level, all other levels of ^{130}Xe which have a γ-ray branch to the ground state also show a much larger branch to the 2^+ state at 536.1 keV.

The 2307.8-keV γ ray could feed the 536.1-keV level from a level at 2843.9 keV but the small Q_β would result in a low log*ft* value of 6.6, hence the γ ray is placed as feeding the ground. We have examined our spectra carefully for any other γ rays that would aid in the placement of these γ rays and found none. The same arguments apply to the weaker γ rays at 1989.1 and 2029.3 keV although we have not made any tentative placement of these γ rays in Fig. 1.

Spin and parity assignments of 1^+, 2^+ are made for the three levels at 2150.2, 2385.5, and 2502.2 keV as these are: (1) fed by both 1^+ ^{130}Cs and 2^+ $^{130}I^m$, (2) strongly fed by one of the two isotopes, and (3) show a ground-state transition as well. The allowed β feeding of the 2150.2-keV level and its γ branches to states of 0^+, 2^+, and 4^+ spin and parity permit a tentative 2^+ assignment for that level. The 2296.2-keV level is moderately fed in the $^{130}I^m$ decay and also exhibits a ground-state transition which allows a tentative 1^+, 2^+ assignment for this level.

IV. DISCUSSION

We have tabulated the major β and γ characteristics of the low-spin ($J \leq 3$) states of ^{130}Xe in Table II. The spin and parity of ^{129}Xe are $\frac{1}{2}^+$, hence the capture states in ^{130}Xe are 0^+ and 1^+. For the resonance-neutron capture the (9.47 eV)-resonance spin and parity are 1^+.[7] Assuming *E*1, *M*1, and *E*2 radiation from the capture states,

TABLE II. Characteristics of low-spin ^{130}Xe levels between 2.0 and 2.8 MeV.

Level	Log*ft* value		$^{129}Xe(n,\gamma)^{130}Xe$ [a]		γ-ray branch (%)	
(keV)	1^+ ^{130}Cs	2^+ $^{130}I^m$	$^{129}Xe(\text{res } n,\gamma)^{130}Xe$ [b]	g.s.	2_1^+	2_2^+
2017	6.2		Yes [b]		6	94
2150	6.1	6.3	Yes [b]	4	89	7
2223	6.1		Yes [b]		100	
2243	6.2		Yes [b]		100	
2296		7.4	Yes [b]	11	85	4
2307		8.5		100		
2386	6.3	8.2	Yes [a,b]		45	55
2494	7.0	6.9			100	
2502	6.9	6.2	Yes [b]	12	51	36
2533	5.8				100	
2544		7.5	Yes [a]	9	91	
2628	6.8	7.3			100	
2632			Yes [a,b]			
2637		7.1			100	
2644		6.7			47	49
2662			Yes [a]			
2726			Yes [a]			
2762		7.4	Yes [b]	100		

[a] Reference 3.

[b] Reference 7.

levels with $0^{\pm}$, $1^{\pm}$, $2^{\pm}$, and 3^+ could be fed. This density of states is considerably higher than can be accounted for by the two-particle states tabulated by Hopke *et al.*[4] who listed two 1^+ states, six 2^+ states, and one 3^+ state. Several other types of excitation are possible, including multiple-phonon states, two-quasiparticle-plus-phonon states, and octupole-plus-quadrupole-phonon states. Evidence for these complex structures is seen in the weak decay to the ground state for most levels and the presence of several strong branches to the second 2^+ state. With a pairing energy of ~1.9 MeV it is not likely that four quasiparticle levels will be pulled down from near 3.8 MeV into the range we observe below 2.8 MeV.

The five states fed by 1^+ ^{130}Cs and not fed by 2^+ $^{130}\mathrm{I}^m$ raise interesting questions. All are candidates for 0^+ assignments. Hopke *et al.*[4] proposed such assignments for the two lower states at 1794 and 2017 keV and utilized the branching to the first and second 2^+ levels to interpret them as members of the two-phonon triplet and three-phonon quintriplet, respectively. The other three states are fed strongly by ^{130}Cs, the first 2^+ state is fed strongly but only the 2243-keV state is fed in the capture-γ experiment. These states could be interpreted as 0^+ states whose structure is predominantly that of a 2^+ two-quasiparticle state coupled to the 2^+ core excitation.

Three states at 1840, 2662, and 2726 keV were observed by Groshev *et al.*[3] and not seen in any of the radioactive-decay studies nor by Gelletly *et al.*[7] We can set lower limits of ≈8.0 for the β feeding to the upper two levels (assuming decay would be to the g.s. or 536-keV level). These states could be 0^+ states or negative-parity states. Our failure to observe the 1840 state is more difficult to understand. Such a state might deexcite by γ rays at 1840, 1304, or 718 keV. In view of our ability to observe very weak γ rays at 1849.3 ($I = 0.11$), 1174.22 ($I = 0.081$), and 837 ($I = 0.051$) keV, we can set a lower limit on the log*ft* of ≈9.0 for β feeding of any such level. Because of the unlikelihood of low-spin negative-parity states at that energy, either a 0^+ assignment and/or an unusual configuration in which the β-decay matrix elements cancel can be suggested. Alternately, the 7.415-keV capture γ ray might result from an impurity and no level would be present at 1840 keV in ^{130}Xe.

A tentative 3^+ assignment for the level at 1632 keV has been proposed previously in Ref. 4, as the possibility of 4^+ was considered less likely on the basis of weak or nonfeeding ($\log ft \geq 10.2$) from 5^+ $^{130}\mathrm{I}^g$. The presence of a branch[4] to the 1632-keV level (albeit weak) from the level at 2362 shown by the angular-correlation results of Bakiev *et al.*[5] to be 5^+ is consistent with either possibility and surely eliminates the 2^+ possibility. Observation in this work of decay to the 1632-keV level from 2^+ $^{130}\mathrm{I}^m$ ($\log ft = 9.1$) confirms the 3^+ assignment. The very high log*ft* value similar to the value[4,5] for the decay of 5^+ $^{130}\mathrm{I}^g$ to the 4^+ level at 1204 keV suggests considerable collective character for this state.

The decay scheme of Bakiev *et al.*[5] may now be reviewed in the light of the results of this work and that of Hopke *et al.*[4] Alternate placement in Ref. 4 of the 877-, 893-, and 1424-keV γ rays reported in Ref. 5, and failure to observe γ rays of 934 or 1202 keV in this work or the work of Ref. 4 removes the evidence for the levels at 1413.4, 2837, and 2878 keV given in Ref. 5. The 2223- and 2243-keV levels are not found to be populated in the decay of $^{130}\mathrm{I}^m$.

The over-all framework for an adequate understanding of the levels of ^{130}Xe remains uncertain. The variable-moment-of-inertia (VMI) approach[8] and its extensions[9] initially offered an attractive account for the 0^+, 2^+, 4^+, 6^+, 8^+ sequence. The more recent placement[1] of the 8^+ level at 2696 keV rather than 2785 keV (the former placement[10] has been identified as arising from a Mn γ ray) now renders a VMI fit to that sequence impossible. Were the quasirotational approach suggested by Sakai[11] and discussed by Hopke *et al.*[4] to be useful, we should have expected that β decay of 2^+ $^{130}\mathrm{I}^m$ should have populated the 2^+ member of the quasi-β band and which would in turn partially decay to the 0^+ quasi-β band head. In neither of these approaches is there a mechanism to account for the high density of states found thus far in ^{130}Xe (28 states between 2.00 and 2.82 MeV). As mentioned above, various combinations of collective and two-quasiparticle states can be written down to indicate origins for the observed density. Quantitative evaluations of their positions and decay characteristics are not available, however, as most theoretical work on ^{130}Xe has been directed at the more narrow and less complicated problem of accounting for the yrast states.

We conclude by noting that the confirmed presence of 3^+ levels lowered below the other two-quasiparticle or three-phonon levels in ^{130}Xe (1632 keV), ^{132}Xe (1803 keV), and ^{134}Xe (1920 keV) represent a feature of nuclear structure not observed at lower Z for near-spherical nuclei. In particular, no such states are noted in isobaric even-even Te nuclides or in Te nuclides (such as ^{124}Te) whose first 2^+ state lies at an energy comparable to the above Xe nuclides. We suggest that an understanding of the character of this state will be a step in the direction of an improved over-all picture of even-even Xe nuclei.

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