Acad. Sci. USSR, Phys. Ser. 29, 755 (1966)].
[5]H. R. Koch, Z. Physik 192, 142 (1966).
[6]R. A. Harlan and R. K. Sheline, Phys. Rev. 160, 1005 (1967).
[7]The assumption that a ratio with D_i in the denominator is a relevant quantity follows from the single-particle description of high-energy radiative transitions: J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley & Sons, Inc., New York, 1952), p. 639.
[8]G. A. Bartholomew, Ann. Rev. Nucl. Sci. 11, 259 (1961).
[9]P. Axel, Phys. Rev. 126, 671 (1962).
[10]C. E. Porter and R. G. Thomas, Phys. Rev. 104, 483 (1956).
[11]There are slight indications in the data that the indeterminate intensity is formed by transitions to two states at about 1431 keV.

HIGH-SPIN ISOMER Ir^{194m_2} PRODUCED BY TRIPLE NEUTRON CAPTURE*

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A 171-day high-spin ($I \geq 10$) isomer was discovered in Ir^{194}. It is predominantly formed by three successive neutron captures from Ir^{191}, via successively higher spin states in Ir^{192} ($I = 4$) and Ir^{193m} ($I = \frac{11}{2}$). The isomer decays by γ decay chiefly to a 2438-keV state in Pt^{194}, which is depopulated by two parallel branches. The more intense branch proceeds through a "ground-state band" ($8^+ \to 6^+ \to 4^+ \to 2^+ \to 0^+$) whose level energies indicate that Pt^{194} is a somewhat deformed and very "soft" nucleus.

High-spin levels have been found in several odd-odd Ir isotopes: e.g., the 3.2-hr isomeric state[1] in Ir^{190} has been tentatively assigned as 11^-,[2] and the 650-yr isomer[3,4] of Ir^{192} as 9^+. Both Ir^{190} and Ir^{192} triple isomers.

In Ir^{194} a 0.032s isomer[5] at 197 keV[6] decays by a two-step isomeric transition to the 17.4-h (1^-) ground state. A probable spin-parity assignment 5^+ was recently reported[6] for this isomer.

A high-spin isomer of Ir^{194} with a half-life longer than a minute had been searched for by bombarding enriched Ir^{193} with slow neutrons, but none was found. It was therefore assumed that such an isomer, if it exists, must have a long half-life and a small production cross section. Hence, a further attempt to search for Ir^{194m_2} was made by irradiating 4.4 mg of enriched Ir^{193} (89.1% Ir^{193}, 10.9% Ir^{191}) with slow neutrons from the Materials Testing Reactor. The time integral of the neutron flux received by the sample was 5.3×10^{21} neutrons/cm^2. Simultaneously, 2.7 mg of enriched Ir^{191} (94.7% Ir^{191}, 5.3% Ir^{193}) were bombarded, both as a control and for the further study of Ir^{192m_2}. In order to permit the decay of the strong 74-day Ir^{192} in both samples, their study was postponed for a period of 62 months, when, surprisingly, the γ spectra from both samples were found to be essentially identical and due to a new high-spin isomer Ir^{194m_2} decaying by β decay to a hitherto unknown high-spin state (≥ 9) in Pt^{194}. The activity from the Ir^{191} target (~0.1 μCi) was found to be ~5 times stronger than that from the Ir^{193} target. These findings can be explained by assuming that the new activity is produced by three successive neutron captures leading to successively higher spin states in the product nuclei[7,8]:

$$Ir^{191}(\tfrac{3}{2}^+) \xrightarrow{910\text{ b}} Ir^{192}[4(-)](74\text{ day}) \xrightarrow{1500\text{ b}} Ir^{193}(\tfrac{11}{2}^-)(12\text{ day}) \xrightarrow{\geq 35\text{ mb}} Ir^{194m_2}(\geq 10).$$

Hence, a high neutron flux is essential for the production of this isomer in quantities which permit its observation above the inevitable background of 74-day Ir^{192}. The neutron-capture cross section of 35 mb which leads to the formation of Ir^{194m_2} is based on the assumption that the capture cross section leading to the Ir^{194} ground state is sufficiently small ($\lesssim 140$ b) to affect the computed cross-section value by $\lesssim 10\%$. The very low upper limit for the presence of Ir^{192m_2} in this source also implies a high neutron-capture cross section in Ir^{192m_2}.

The new activity was identified by its two strongest γ rays of 328.5 and 482.6 keV, which are known as the $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions in Pt^{194}.

By chemical separation of Pt from the Ir sample it was established that the long-lived isomer occurs in Ir^{194} and not in Pt^{194}. As a control for the efficiency of the Pt separation, the L x rays from the long-lived (<500-yr) Pt^{193} were employed.[9] (The half-life of a possible isomeric state in Pt^{194} populated by β decay was found to be <30 min.)

The γ rays from the new activity were investigated with high resolution Ge(Li) detectors, both in singles and by two-parameter analysis of γ-γ coincidences. Similar coincidence measurements between electrons observed by means of a Si(Li) counter and γ rays detected either with a Ge(Li) counter or with a NaI counter were performed. Further, the K and L x-ray region was explored by means of a Si(Li) detector. The half-life (171 ± 11 day) was determined by measuring the decay of the 482.6-keV γ ray relative to γ rays from Ag^{110m} (253-day) and Eu^{154} (16-yr) impurities[10] of comparable intensities. Table I lists the energies (±0.5 keV) (column 1) and intensities (±~5%) (column 2) of the γ rays from Ir^{194m_2}.

Typical γ-ray coincidence spectra derived from the two-parameter γ-γ coincidence measurements are shown in Fig. 1. The Ir^{194m_2} isomer decays mainly to a 2438-keV state in Pt^{194}, which is de-excited by two parallel cascades. The more intense cascade (≈64% of the 328.5-keV γ rays) proceeds via three transitions of 338.8, 687.8, and 600.5 keV to the 4^+ state at 811.1 keV. The less intense cascade proceeds to the 4^+ state via four transitions, two of which are indistinguishable in energy, 562.4 keV, while the other two have energies of 390.8 and 111.7 keV. The intensity of this cascade is ≈36% of the intensity of the 328.5-keV γ rays, with the exception of the 111.7-keV line, which is only ~$\frac{1}{4}$ as intense as the three other lines. From studies of the conversion electron spectrum with a Si(Li) detector, it was possible to derive K conversion coefficients for most of the observed transitions by comparing K-line intensities with the K-line intensities of the well-known 328.5- and 482.6-keV $E2$ transitions and by using the results of our γ-ray intensity measurements. These K-shell conversion coefficients are listed in Table I (column 3), together with theoretical K-conversion coefficients[11] for $E1$, $M1$, and $E2$ multipoles (columns 4, 5, and 6, respectively) and the derived multi-

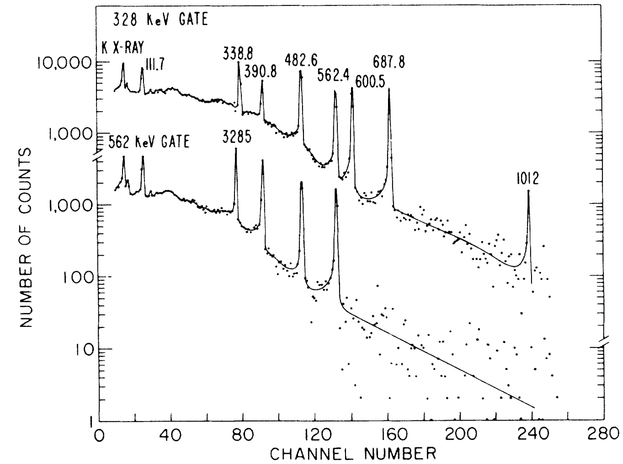

FIG. 1. Coincidence spectra obtained with two Li-drifted Ge counters and a two-parameter 16 384-channel analyzer. The spectra shown are those obtained in coincidence with the 328.5- and 562.4-keV γ rays, corrected for the Compton background under each line

Table I. Energies, intensities, and multipolarities of transitions in Pt^{194} from the decay of Ir^{194m_2}(171 day).

Energy (keV)	γ-ray intensity (relative)	$10^2\times$ (experimental K-shell conversion coefficient)	Theoretical K-shell conversion coefficient $E1$	$M1$	$E2$	Multi-polarity	α_{tot}[c]	Transition intensity
111.7	8.85	···	0.255	4.05	0.60	($E2$)	3.4	38.9
328.5	92.8	4.9[a]	···	···	4.9×10^{-2}	$E2$	0.078	100
338.8	55.1	4.9 ± 0.6	1.62×10^{-2}	0.185	4.5×10^{-2}	$E2$	0.070	59.0
390.8	35.1	1.5 ± 0.5	1.13×10^{-2}	0.128	3.2×10^{-2}	$E1$	0.014	35.6
482.6	96.9	1.97[a]	···	···	1.97×10^{-2}	$E2$	0.027	99.5
562.4	35.2	0.64 ± 0.17[b]				$E1$	0.007	35.4
	69.9	1.14 ± 0.30	0.54×10^{-2}	4.7×10^{-2}	1.38×10^{-2}			
562.4	34.7	1.64 ± 0.43[b]				$E2$	0.019	35.4
600.5	62.3	1.47 ± 0.26	0.48×10^{-2}	4.0×10^{-2}	1.19×10^{-2}	$E2$	0.016	63.8
687.8	59.1	1.04 ± 0.25	0.36×10^{-2}	2.8×10^{-2}	0.89×10^{-2}	$E2$	0.012	59.8
1011.8	3.6							3.6

[a]Theoretical conversion coefficients of known $E2$ transitions, to which other lines are normalized.

[b]Individual conversion coefficients of the two 562.4-keV transitions are derived by assuming $E1$ and $E2$ multipolarities for the individual transitions.

[c]Total conversion coefficient is theoretical value based on multipolarity, derived from K and L conversion coefficients (see Ref. 11).

polarity for each transition (column 7). Although source thickness effects precluded any definitive electron measurements for the 111.7-keV transition, a total conversion coefficient of about 3 is deduced from the γ-ray intensity data, showing that this transition is mainly $E2$.

From the systematic occurrence of collective bands in even-even Pt nuclei[12] found by means of the $(\alpha, 2n)$ reaction, it may be concluded that the sequence of transitions in the more intense cascade is as shown in Fig. 2. The 338.8-keV transition proceeds from an intrinsic state (probably 10^+) to the 8^+ state of a "ground-state band." The energy of the transition $6^+ \rightarrow 4^+$ (600.5 keV) differs from that given in Ref. 12 (570 ± 10 keV).[13] The transition $8^+ \rightarrow 6^+$ has not been observed previously. The level energies of this ground-state band deviate appreciably from the $I(I+1)$ rule, but can be fitted readily by a semiempirical analysis of collective bands recently proposed.[14] A weak transition (3.6%) of 1011.8 keV found to be in coincidence with the 600.5, 482.6, and 328.5-keV transitions probably establishes a level at 2423 keV. A 324-keV γ ray observed in the singles spectrum (too weak to be observed in coincidence) probably originates from this state. It is not known whether the 1011.8-keV transition is preceded (or possibly followed) by an undiscovered 14.8-keV transition or whether the 2423-keV level is populated by β rays. No 14.8-keV photons were observed although the intensity would have been high enough to be observed if (a) the transition were $E1$, (b) the $E1$ conversion were normal ($\alpha_T \simeq 18.1$),[15] and (c) only the 2438-keV state were populated by β decay. The sequence of the transitions in the weaker cascade, starting from the 2438-keV state, is 390.8, 111.7, 562.4, and 562.4 keV. This order follows from the intensities of these γ rays as observed[16] in the $(\alpha, 2n)$ reaction.

The apparent retardation of the 391-keV transition (this $E1$ transition has a transition rate comparable with that of the 338-keV $E2$ transition) indicates a quasiparticle description for the 2438-keV state different from the descriptions for the states of the less intense branch. The 2438-keV state is most likely a two-proton configuration $([505\uparrow]_{11/2}-, [514\uparrow]_{9/2}-)$, while the 2048-keV state may involve to a considerable extent the $[615\uparrow]_{11/2}+, [503\uparrow]_{7/2}-$ two-neutron configuration. Until absolute transition rates have been measured, it is perhaps not useful to speculate further about possible configuration assignments. However, it is of interest to note that this is the first energy spectrum of a moderately heavy or heavy even-even nucleus in which two quasiparticle states of energies comparable with the energies of the 6^+ and 8^+ states of the ground state band have been shown to exist.

A search of the Ge(Li) γ-ray spectrum was

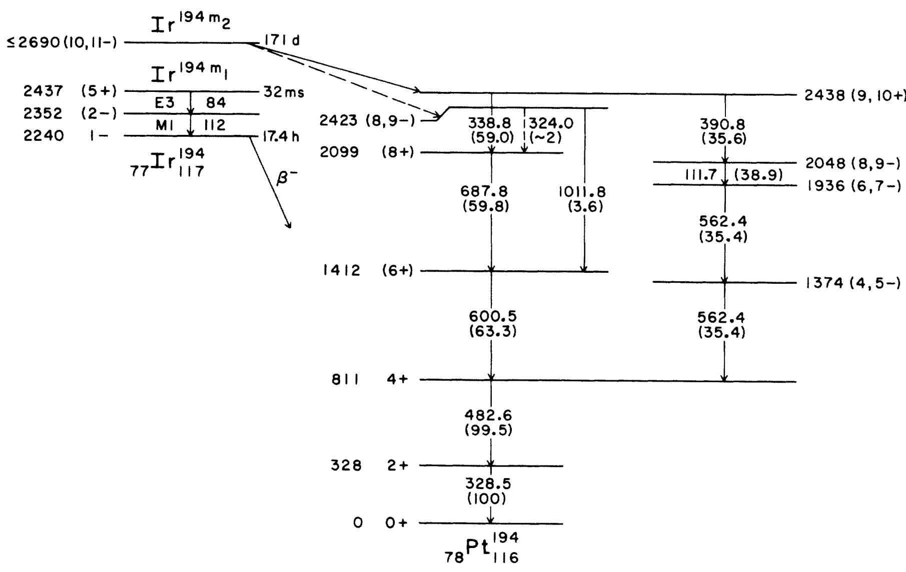

FIG. 2. Proposed decay scheme of Ir^{194m_2}. The level energies are given in keV. Energies and spin and parity assignments of the first two excited states of Ir^{194} are taken from Ref. 6. The numbers in parentheses are intensities given in percent per disintegration. See text.

made for all "interband" transitions which might occur on the basis of the level scheme of Fig. 2. The possible transitions of 163, 376, 488, 524, 636, and 726 keV, if present, all have γ-ray intensities which are less than 0.1% of the 328.5-keV γ-ray intensity. In addition, a search of the Si(Li) low-energy γ-ray spectrum showed that the possible 38- and 51-keV transitions, if present, have γ-ray intensities which are less than 0.2 and 0.4%, respectively, of the 328.5-keV intensity. The absence of such "interband" transitions may probably be attributed to the K selection rule.

The thickness of the source, together with the abundance of conversion lines, made a β-ray endpoint determination difficult. However, unless the half-life of the 2438-keV state exceeds a few$\times 10^{-7}$ sec, it is likely that $E_{\beta\,\max} \leq 250$ keV. This places the Ir^{194m_2} isomer ≤ 450 keV above the 17.4-h ground state and $\lesssim 250$ keV above the 0.03-sec state. No isomeric transition to this state has been observed; the lower limit for its partial half-life is $\approx 10^8$ sec. This implies a spin change >4, unless the isomeric transition is exceptionally retarded. This is in agreement with the spin assignments which are obtained from the available Nilsson orbitals in this region. For $E_{\beta\,\max} \leq 250$ keV one obtains $\ln ft \leq 7.3$. Hence, the β transition to the 2438-keV state is either allowed or first forbidden. Since the spin of the 2438-keV state in Pt^{194} must be 9 or 10, it appears probable that the spin of the Ir isomer is 10 or 11. A spin and parity of 11^- arises naturally from the coupling of neutron orbital $[615\uparrow]_{11/2+}$ to the proton orbital $[505\uparrow]_{11/2-}$. The large difference in spin between Ir^{193} ($\frac{11}{2}$) and Ir^{194m_2} may be responsible for the small reaction cross section for the reaction Ir^{193} (12 day)$+n \to Ir^{194m_2}$.

The potential energy of deformation for Pt^{194} has recently been calculated with the pairing-plus-quandrupole model.[17] The lowest potential minimum occurs for a slightly deformed, oblate shape, but this minimum is very shallow and the wave function is smeared out over all possible shapes: prolate, spherical, asymmetric, and oblate. In qualitative agreement with this result, the semiempirical analysis[14] of the ground-state band of Pt^{194} as established here (Fig. 2) yields a "ground-state moment of inertia" $\sim\frac{1}{6}$ that of the most strongly deformed nuclei and a very large "softness parameter." The softness may be attributed to the "coexistence" of the ground-state band with quasiparticle states.

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[1]A. H. Aten, G. D. Feyfer, M. J. Stark, and A. H. Wapstra, Physica 21, 740, 990 (1955); G. Scharff-Goldhaber, D. E. Alburger, G. Harbottle, and M. Mc Keown, Phys. Rev. 111, 913 (1958).

[2]B. Harmatz and T. H. Handley, Nucl. Phys. 56, 1 (1964).

[3]G. Scharff-Goldhaber and M. McKeown, Phys. Rev. Letters 3, 47 (1959).

[4]G. Harbottle, Nucl. Phys. 41, 604 (1963).

[5]K. F. Alexander and H. F. Brinkmann, Z. Naturforsch. 16a, 210 (1961).

[6]A. Lundan and A. Siivola, Nucl. Phys. A106, 417 (1967).

[7]B. Keisch, Phys. Rev. 129, 769 (1963).

[8]F. Boehm and P. Marmier, Phys. Rev. 105, 974 (1957).

[9]The presence of this activity in the source is attributed to the reaction $Pt^{192}+n_{\rm th}$; Pt^{192} is formed by the decay of Ir^{192} (74 day).

[10]The following other impurities were present in the source: Ag^{108} (>5 yr), Eu^{155} (1.81 yr) (both formed by slow neutron capture). Rh^{102} (206 day) presumably formed by fast neutrons gives a Rh^{103} impurity as well as Th^{101} (3 yr).

[11]L. A. Sliv and I. M. Band, in Alpha-, Beta-, and Gamma-Ray Spectroscopy, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, The Netherlands, 1965), Vol. 2, p. 1639.

[12]N. Lark and H. Morinaga, Nucl. Phys. 63, 466 (1955).

[13]However, a recent unpublished study of the reaction $Os^{192}(\alpha,2n)$ whose results were kindly communicated to us by Dr. R. Diamond confirms the energy of 600 keV.

[14]M. Mariscotti, Brookhaven National Laboratory Report No. BNL 11838 (unpublished); M. Mariscotti and G. Scharff-Goldhaber, to be published.

[15]R. S. Hager and E. C. Seltzer, California Institute of Technology Report No. CALT-63-60, 1967 (unpublished).

[16]We are grateful to R. Diamond, F. Stephens, and D. Ward, who informed us of their unpublished results.

[17]K. Kumar and M. Baranger, Nucl. Phys. A110, 529 (1968).