417 (1969)].
[16]Yu. A. Muzychka, Yad. Fiz. 10, 113 (1969) [Sov. J. Nucl. Phys. 10, 66 (1970)].
[17]S. G. Nilsson *et al.*, Nucl. Phys. A131, 1 (1969).
[18]A. Łukasiak, A. Sobiczewski, and W. Stepień-Rudzka, Warsaw Report "P," No. 1293/VII/PL, 1971 (to be published); A. Sobiczewski, private communication.
[19]M. Brack, J. Damgaard, H.-C. Pauli, A. Stenholm-Jensen, V. M. Strutinsky, and C. Y. Wong, to be published.
[20]U. Mosel and W. Greiner, Z. Phys. 222, 261 (1969).
[21]W. J. Swiatecki, unpublished.

New Five-Quasiparticle Isomeric State in ^{177}Hf†

T. E. Ward and P. E. Haustein
Department of Chemistry, Brookhaven National Laboratory, Upton, New York 11973
(Received 16 July 1971)

A new high-spin isomer ^{177m_2}Hf has been produced via the reactions ^{176}Yb(α, 3n)^{177}Hf and ^{186}W(p,$p\alpha$5n)^{177}Hf. It is interpreted as a $K^\pi = \frac{37}{2}^-$ five-quasiparticle state. Seven γ rays attributed to the decay of this new isomer, and the γ radiation from 1.1-sec ^{177m_1}Hf in equilibrium, decayed with a (51.6 ± 1.6)-min half-life. These γ rays result from de-excitation of an isomeric level in ^{177}Hf at 2739.7 keV to the rotational band members of the $K^\pi = \frac{23}{2}^+$ isomeric state.

A new high-spin isomer, ^{177m_2}Hf ($T_{1/2}$ = 51.6 min), was observed and interpreted as a $K^\pi = \frac{37}{2}^-$ five-quasiparticle state. This isomer represents the highest spin state reported to date having an appreciable half-life ($T_{1/2}$ greater than a few microseconds) and is the first five-quasiparticle state observed in deformed nuclei. A number of other quasiparticle isomeric states are known[1-4] in the hafnium region, i.e., two-quasiparticle $K^\pi = 8^-$ isomers of ^{176}Hf, ^{178}Hf, ^{180}Hf, and ^{182}Hf; three-quasiparticle isomers of ^{177}Lu ($K^\pi = \frac{23}{2}^-$), ^{177}Hf ($K^\pi = \frac{23}{2}^+$), and ^{179}Hf ($K^\pi = \frac{25}{2}^-$)[5,6]; and a four-quasiparticle isomer of ^{178}Hf ($K^\pi = 16^+$).[7] These two-, three-, and four-quasiparticle states have configurations involving two or more of the following Nilsson states: $\frac{7}{2}-[514]_n$, $\frac{9}{2}+[624]_n$, $\frac{7}{2}+[404]_p$, and $\frac{9}{2}-[514]_p$.

Sources of ^{177m_2}Hf were produced by irradiation of isotopically enriched $^{186}WO_3$ (97%) and $^{176}Yb_2O_3$ (96%) with 96-MeV protons and 46-MeV α particles, respectively making use of the reactions ^{186}W(p, $p\alpha$5n)^{177}Hf and ^{176}Yb(α, 3n)^{177}Hf. Cross sections for the production reactions at these energies were estimated to be ~50 and ~400 μb for protons and α particles, respectively. The radiochemical separation of Hf from irradiated tungsten and ytterbium targets was identical to the one used in Ref. 4. The sources of hafnium obtained were highly decontaminated from neighboring elements. In one case, the Hf source was isotopically mass separated. The samples were counted with Ge(Li) detectors which had been calibrated for energy and efficiency with International Atomic Energy Agency standard sources. Analysis of the γ-ray spectra was performed by means of a modified version of the computer code BRUTAL. The program CLSQ[9] was used for γ-ray decay curve resolutions.

In Table I are listed the γ-ray energies and relative intensities for ^{177m_2}Hf. We observed 25 additional lines and assigned them to transitions of the $K^\pi = \frac{23}{2}^+$ three-quasiparticle isomer of ^{177}Hf which was in equilibrium. The decay of 1.1-sec ^{177m_1}Hf has been studied[10,11] quite well from the β decay of 161-d ^{177m}Lu ($K^\pi = \frac{23}{3}^-$), and the γ-ray energies and relative intensities measured in the present study were within the experimental errors of those previous measurements. The averaged γ-ray half-life of those lines listed in Table I and the additional 25 lines from ^{177m_1}Hf in equilibrium were determined to be 51.6 ± 1.6 min. The new activity was assigned as an isomer of ^{177}Hf based on the following considerations: (a) chemical identification with hafnium, (b) observation of ^{177m_1}Hf (1.1 sec) in equilibrium, and (c) isotopic mass separation and identification with A = 177.

In Fig. 1 is shown the proposed isomeric decay scheme of ^{177m_2}Hf. The decay of ^{177m_1}Hf (1.1 sec) has been omitted for simplicity; its well-known decay scheme can be found in Refs. 1, 10, and 11. The isomeric state at 2739.7 keV was established from energy-sum and relative γ-ray intensity considerations. The γ rays of 277.1, 294.9, 311.3, 326.6, 572.3, 606.5, and 638.0 keV fit well for the expected crossover and cascade transitions of the rotational band members

TABLE I. γ-ray energies and intensities of ^{177m_2}Hf.

E_γ (keV)[a]	Relative γ-ray intensity	Multipolarity[c]	Total conversion coefficient (α)	Relative transition intensity[d]
214.4	57.0(5.2)	$E3$	1.44	104.5(9.5)
277.1	=100.0[b]	$M1+\sim10\%\,E2$	0.234	92.5
294.9	86.6(8.3)	$M1+\ 9.1\%\,E2$	0.197	77.0(7.4)
311.3	77.6(7.8)	$M1+\ 8.3\%\,E2$	0.164	67.1(6.7)
326.6	93.1(8.9)	$M1+\ 7.8\%\,E2$	0.144	80.1(7.7)
572.3	10.0(1.1)	$E2$	0.013	7.5
606.5	17.3(1.7)	$E2$	0.010	13.3(1.3)
638.0	30.3(2.8)	$E2$	0.009	23.3(2.2)

[a]Error in γ-ray energy is ±0.4 keV.
[b]Normalized to 100 units.
[c]See text and Table II for explanation of assignment.
[d]Normalized to $I_{tot}(277.1)+I_{tot}(572.3)=100$ units.

up to $I=\frac{31}{2}$, built on the $K^\pi=\frac{23}{2}^+$ isomeric state. This new high-spin isomer is interpreted as being a $K^\pi=\frac{37}{2}^-$ five-quasiparticle isomer with a possible Nilsson configuration of $\frac{7}{2}+[404]_p$, $\frac{9}{2}-[514]_p$, $\frac{7}{2}-[514]_n$, $\frac{9}{2}+[624]_n$, $\frac{5}{2}-[512]_n$. One can view the formation of this five-quasiparticle state as the breaking of the $\frac{5}{2}-[512]$ neutron pair, promotion of one of the neutrons to the $\frac{9}{2}+[624]_n$ state, and combining the hole and particle states with the $K^\pi=\frac{23}{2}^+$ three-quasiparticle configuration of $\frac{7}{2}+[404]_p$, $\frac{9}{2}-[514]_p$, $\frac{7}{2}-[514]_n$.

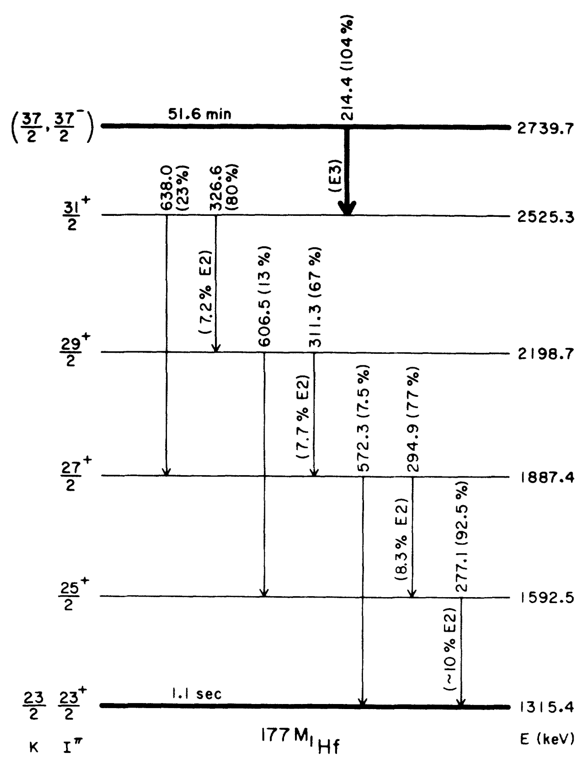

FIG. 1. Proposed isomeric decay scheme of ^{177m_2}Hf to the $K^\pi=\frac{23}{2}^+$ rotational band.

If the spin/parity of the new isomeric state is $\frac{37}{2}^-$, then the 214.4-keV γ ray assigned to the isomeric transition would become a highly retarded K-forbidden $E3$ transition. The hindrance factor[12] H calculated for the $E3$ transition would be $\sim2.4\times10^5$, or a factor of ~22 for each degree of K forbiddeness ($\nu=\Delta K-L$). Such a hindrance factor would be expected for a transition between states with relatively pure K quantum numbers.

The balance of population and depopulation of the levels shown in Fig. 1 is in good agreement. The relative total transition intensities have been calculated from the measured γ-ray intensities using the conversion coefficients tabulated by Hager and Seltzer[13] and the $E2$ admixtures for the $\Delta I=1$ transitions which were determined from the crossover-to-cascade intensity ratios by the method of Alexander, Boehm, and Kankeleit.[10] We have used the lowest three energy levels of the $K^\pi=\frac{23}{2}^+$ band in the formula

$$E_I=E_0+AI(I+1)+BI^2(I+1)^2,$$

and calculated $A=12.06$ keV and $B=-3.11$ eV. In Table II we have listed some of the rotational-model properties calculated from the crossover-to-cascade intensity ratios λ of the $K^\pi=\frac{23}{2}^+$ rotational band. The $E2/M1$ mixing ratios δ^2 and the quantity $(g_K-g_R)^2/Q_0^2$ for the three transitions $I\to I-1$ within the $K^\pi=\frac{23}{2}^+$ band are about what one would expect from rotational-model predictions. Detailed studies of this new high-spin isomer are in progress and will be reported at a later date.

The authors would like to acknowledge the

TABLE II. The g factors and branching ratios for the $K^{\pi}=\frac{23}{2}^{+}$ rotational band in ^{177}Hf. λ is the experimental ratio between crossover ($I \rightarrow I-2$) and cascade ($I \rightarrow I-1$) transitions, δ^2 is the $E2/M1$ mixing ratio for the transitions $I \rightarrow I-1$, and $(g_K - g_R)^2/Q_0^2$ is a rotational-model parameter.

I	λ	δ^2	$10^3(g_K-g_R)^2/Q_0^2$
27/2	0.115(12)	0.091(9)	4.60(46)
29/2	0.229(23)	0.083(8)	4.84(48)
31/2	0.329(33)	0.078(8)	5.01(50)

thoughtful advice and encouragement of Dr. J. B. Cumming and Dr. S. Katcoff and the helpful assistance of Dr. Y. Y. Chu in the mass separation of the Hf sources. Assistance provided by the operators of the Brookhaven Linac and cyclotron facilities in obtaining irradiations is gratefully acknowledged.

†Research supported by the Advanced Research Projects Agency and the U. S. Atomic Energy Commission.

[1]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967), 6th ed.

[2]J. Børggreen, N. J. S. Hansen, J. Pedersen, L. Westgaard, J. Zylicz, and S. Bǿrnholm, Nucl. Phys. A96, 561 (1967).

[3]S. G. Nilsson, Kgl. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 29, No. 16 (1955).

[4]T. E. Ward and P. E. Haustein, Phys. Rev. C, to be published.

[5]H. Hübel, R. A. Naumann, M. L. Andersen, J. S. Larsen, O. B. Nielsen, and N. O. Roy Poulsen, Phys. Rev. C 1, 1845 (1970).

[6]H. Hübel, R. A. Naumann, and P. K. Hopke, Phys. Rev. C 2, 1447 (1970).

[7]R. G. Helmer and C. W. Reich, Nucl. Phys. A114, 649 (1968).

[8]R. Gunnick, H. B. Levy, and J. B. Niday, Lawrence Radiation Laboratory Report No. UCID-15140 (unpublished).

[9]J. B. Cumming, National Academy of Sciences, National Research Council, Nuclear Science Series Report No. NAS NS-3107, 1962 (unpublished).

[10]P. Alexander, F. Boehm, and E. Kankeleit, Phys. Rev. 133, B287 (1964).

[11]A. H. Haverfield, F. M. Bernthal, and J. M. Hollander, Nucl. Phys. A94, 337 (1967).

[12]O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Chap. X.

[13]R. S. Hager and E. C. Seltzer, Nucl. Data 4A, 1 (1968).

Study of the Reaction $\pi^- p \rightarrow \pi^+\Delta(1236)^-$ in the Backward Direction at 2.15 to 6 GeV/c*

J. E. Rice,† R. W. Anthony,† C. T. Coffin, E. S. Meanley,‡ and K. M. Terwilliger
University of Michigan, Ann Arbor, Michigan 48104

and

N. R. Stanton‖
University of Michigan, Ann Arbor, Michigan 48104, and Ohio State University, Columbus, Ohio 43210
(Received 21 June 1971)

We present data on the differential cross section for the reaction $\pi^- p \rightarrow \pi^+\Delta(1236)^-$ for π^+ scattered backward near 180°, $-0.002 > u - u_{max} \gtrsim -0.09$ (GeV/c)^2, with incident π^- beam momenta between 2.15 and 6 GeV/c. The differential cross section exhibits a sharp backward dip which appears to persist over this range of incident momenta.

The results presented here are from an optical spark-chamber experiment run at the Argonne National Laboratory zero gradient synchrotron. The experiment has been described briefly in previous publications.[1,2] The momentum spectra of backscattered $\pi^\pm$ from incident π^- on protons were measured with a large-aperture single-arm spectrometer. Data were taken at eleven beam momenta from 2.15 to 6 GeV/c.

Our published results at 2.15 GeV/c [1] indicated a significant backward cross section for the reaction $\pi^- p \rightarrow \pi^+\Delta(1236)^-$; the differential cross section dips sharply at 180°, similar to backward $\pi^- p$ elastic scattering at the same beam momentum. A backward dip also has been observed in a bubble-chamber study of the equivalent charge-symmetric reaction $\pi^+ n \rightarrow \pi^-\Delta(1236)^{++}$, with incident beam momenta 1.9 to 2.5 GeV/c.[3,4] Some evidence that this effect continues to higher momenta is indicated in our new data on the reaction $\pi^- p \rightarrow \pi^+ M^-$ in the backward direction from 2.5 to 6 GeV/c. These data are presented in Fig. 1; included are our replotted 2.15-GeV/c results for comparison. The data above 2.15 GeV/c have