Isomer in Iridium-193†

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An 80.19-kev transition with a half-life of 11.9 days and $M4$ multipolarity has been observed in a neutron-irradiated sample of iridium. The corresponding isomeric state has been assigned to Ir^{193}, which is produced by two successive neutron captures in Ir^{191}. A pile-neutron capture cross section of 1500 barns is found for Ir^{192}.

INTRODUCTION

IT is well known from a large number of investigations, particularly from the careful work of Mihelich and de-Shalit[1] that the energy levels of the odd-A isotopes of Ir, Pt, Au, and Hg show many striking regularities. For example, the arrangement of the low-lying energy levels in the odd-proton isotopes Ir^{191}, Ir^{193} and the gold isotopes with mass numbers 193, 195, and 197 is very similar. All of these nuclei have a spin $\frac{3}{2}+$ ground state and a spin $\frac{1}{2}+$ level at an excitation energy of less than 100 kev. In fact, two close-lying states with spin $\frac{3}{2}+$ and $\frac{1}{2}+$ are predicted by the shell model[2] as well as by the Nilsson model[3] for the configuration of the 77th and 79th proton. The models also predict an $11/2-$ state, which has been found in Ir^{191} and in the three odd-A gold isotopes, but had not been reported in Ir^{193}.

Evidence for this $11/2-$ state in Ir^{193} is given by measurements on neutron-irradiated Ir samples as presented in the following section.

METHODS AND RESULTS

A. Beta-Ray Spectrometer Measurements

A few milligrams of metallic iridium have been irradiated for periods of 11 to 14 days at high neutron flux in the Materials Testing Reactor (MTR) at Arco, Idaho. Sources for the beta-ray spectrometer were prepared by vacuum evaporation of the radioactive iridium onto thin mica sheets. The axial-focusing homogeneous-field beta-ray spectrometer was set at a momentum resolution of 0.12%. Measurements at low energy were performed with the semicircular spectrometer.

The measurements were started 5 days after the end of the pile irradiation. Very intense conversion lines due to the decay of Ir^{192} were present. Besides this 74-day activity, which has been studied earlier in this laboratory,[4] pronounced groups of L-subshell lines and of M- and N-conversion lines were observed between 70- and 80-kev electron energy (Fig. 1). The half-life of these lines was determined to be 11.9 ± 0.5 days.

The experimental conversion ratio, $L_{\mathrm{I}}:L_{\mathrm{II}}:L_{\mathrm{III}} = 5.5:1:22.5$, is characteristic for an $M4$ multipole according to the theoretical conversion data by Rose *et al.*[5] Consistent with this assignment is the observed half-life of 11.9 days.[6] From the difference in binding energy between the L- and M-conversion groups it becomes evident that the transition occurs in an iridium atom. Additional evidence that the isomeric state belongs to iridium was given by a chemical separation between Os, Ir, and Pt. The 11.9-day activity was

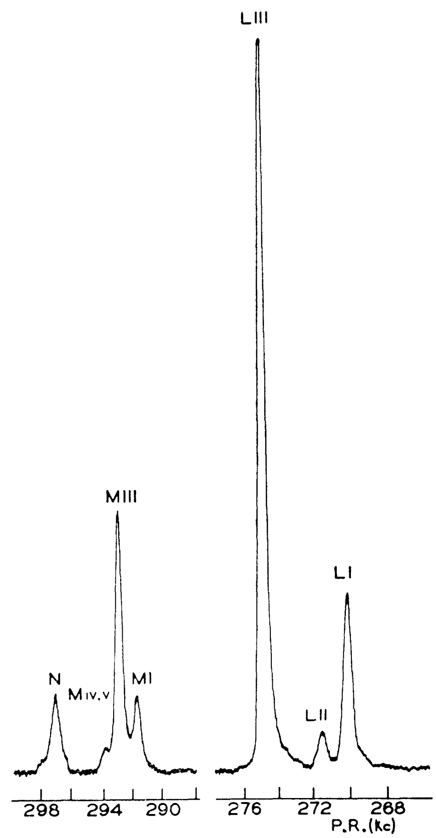

FIG. 1. Internal conversion spectrum of the 80.19-kev gamma line. The beta spectrometer was set at a momentum resolution of 0.12%. (Abscissa: proton-resonance frequency in kc/sec.)

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present in the Ir fraction. Thus the gamma-ray energy of the transition is found to be $E_\gamma = 80.19 \pm 0.05$ kev.

The low-energy spectrum has been recorded down to 2-kev electron energy. No K-conversion peak of the isomeric transition could be seen. This result is not surprising considering the very small K-conversion coefficient of an $M4$ transition at this energy. A very complex L-Auger spectrum composed of more than 20 lines was observed between 5 and 12 kev.

B. Mass-Number Assignment

Samples of enriched Ir^{191} (85.9%) and Ir^{193} (89.1%) obtained from the Stable Isotope Division of the Oak Ridge National Laboratory were irradiated in the MTR. By comparing the intensity of the 80-kev transition to that of a reference line in Ir^{192}, it was possible to conclude that the isomer was produced by a reaction initiating in Ir^{191}. Since the 11.9-day isomer had not been reported by previous investigators,[7] it

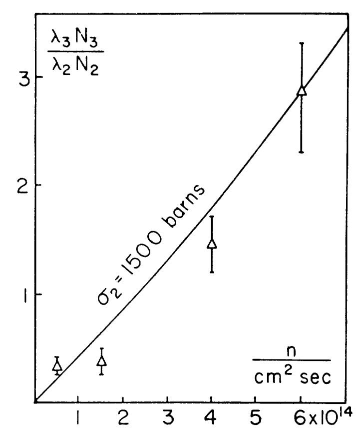

FIG. 2. Ratio of the activation of the 11.9-day isomer to the 74-day Ir^{192} as a function of the pile-neutron flux. Additional errors due to the uncertainties in the neutron-flux value have not been considered in plotting the experimental points. The solid line represents the calculated values if one assumes a capture cross section of 1500 barns for Ir^{192}.

was assumed that it was produced only by a second order reaction in the high neutron flux available in the MTR. In fact, an Ir source irradiated in a flux of 10^{12} neutrons/cm² sec at the Oak Ridge reactor did not show any 80-kev line of observable intensity.

The occurrence of second-order capture reactions has been observed in a few instances. An expression for the population, N_3, of nuclei produced by double neutron capture to the population, N_2, of nuclei produced by single neutron capture has been given by Murray *et al.*[8] This ratio is a function of the neutron flux ψ and the second capture cross section σ_2, as can be seen from Eq. (1) of reference 8.

Irradiations at four different neutron-flux values varying from 0.5×10^{14} to 6×10^{14} neutrons/cm² sec

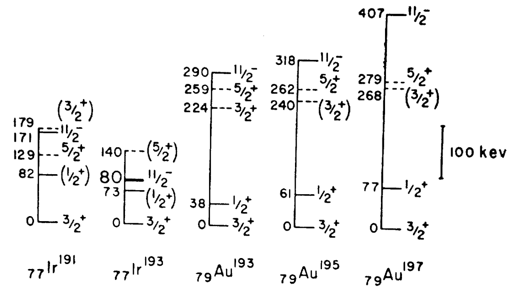

FIG. 3. Comparison of the low-lying levels of some odd-proton isotopes in the neighborhood of Ir^{193}. The first rotational level with spin 5/2 belonging to the ground state band ($K=\frac{3}{2}$), and with spin $\frac{3}{2}$ belonging to the $K=\frac{1}{2}$ band are indicated with dotted lines.

were performed in the MTR. The intensity ratio of the conversion lines of the 80-kev transition to that of the conversion lines of the 296-kev transition in the Ir^{192} decay was measured for each neutron flux value. Since Ir^{192} is produced by single neutron capture, this ratio gives, after one applies corrections for decay fractions and conversion coefficients, the depopulation rate $\lambda_3 N_3/\lambda_2 N_2$, where λ_2 and λ_3 are the respective decay constants. The experimental points are plotted in Fig. 2 as a function of the neutron flux. The corresponding theoretical curve for the intensity ratio has been calculated from Eq. (1) in reference 8. As can be seen, a reasonably good fit to the experimental points is obtained by assuming a neutron-capture cross section in Ir^{192} of 1500 barns. Thus the occurrence of a double capture in Ir^{191} and consequently the mass number assignment 193 for the 11.9-day Ir isomer seems to be established.

DISCUSSION

The 80.19-kev $M4$ line can be interpreted as a transition from an isomeric state with spin $11/2-$ to the ground state of Ir^{193}.

Energy levels in Ir^{193} excited by beta decay of Os^{193} have been investigated by several workers.[9–11] In the recent investigation by de Waard,[9] a first excited level at 73 kev is found. According to Cork *et al.*[10] and Swan and Hill,[11] the 73-kev line is converted in the L_I and L_{II} shell equally strongly. An $M1+E2$ multipole assignment, therefore, seems very likely and the identification of the 73-kev level as the $\frac{1}{2}+$ intrinsic state mentioned in the introduction seems reasonable. In the decay of the 80.19-kev isomeric state, this level is not excited because of the large spin difference.

A summary of the data on low-lying levels in Ir^{193} as compared to those of the neighboring odd-proton isotopes Ir^{191}, Au^{193}, Au^{195}, and Au^{197} is given in Fig. 3.

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In addition to the intrinsic levels with spin $\frac{1}{2}+$ and $11/2-$, some rotational levels of the $K=\frac{1}{2}$ and $K=\frac{3}{2}$ bands are shown. The transition from Ir to Au is characterized by a drop in nuclear deformation and by an overcrossing of the $\frac{3}{2}+$ and $\frac{1}{2}+$ intrinsic states. Considering this fact, the generally smooth behavior of the $\frac{1}{2}$, $\frac{3}{2}(K=\frac{1}{2})$, and $5/2(K=\frac{3}{2})$ levels is worth noting. The $11/2-$ level follows this trend not too rigidly and is somewhat low in Ir^{193} and somewhat high in Au^{197}.

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Atomic Distribution in Liquid Argon by Neutron Diffraction and the Cross Sections of A^{36} and A^{40}

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The angular distribution of 1.04 A neutrons scattered by liquid argon at 84°K is reported. Small-angle scattering in the pattern is accounted for in terms of isotope incoherence using the same sign for the measured values of the scattering lengths of A^{40} and A^{36}. The transmission cross section of A^{36} was measured for 1.04 A neutrons and found to be 77 ± 9 barns corresponding to a scattering cross section of 73 ± 9 barns. The scattering cross section of A^{40} was measured and found to be 0.36 barn. The scattering curve was transformed to the atomic density distribution $4\pi r^2[\rho(r)-\rho_0]$ for the liquid. The function shows only small oscillations about $-4\pi r^2\rho_0$ for spacings out to 3 A. Beyond this the curve oscillates about zero with an amplitude which decreases with increasing radius. The number of neighbors assigned to the first shell of atoms is $8._2$. From a comparison of the position of the density cutoff and first density maximum with that expected for a Lennard-Jones 12:6 potential, it is concluded that the effective potential in the liquid has a broader bowl than that given by the Lennard-Jones 12:6 potential.

INTRODUCTION

A KNOWLEDGE of the atomic distributions in liquids is of importance for the theory of liquids. It should be possible to calculate all the thermodynamic properties of a liquid from a knowledge of the atomic distribution function and the potential function. The liquid argon atomic distribution function has been previously measured by using x-rays,[1–4] and these results have been summarized in a review article by Gingrich.[5] The atomic distributions in the liquid and the vapor have been studied extensively by x-rays over a wide range of pressure and temperature by Eisenstein and Gingrich.[4] They reported radial distribution functions for spacings out to 8 A.

More recently the structure of liquid argon at 86.3°K has been measured by means of neutrons.[6] The atomic distribution was reported for radial separations out to 20 A. The neutron scattering pattern contained considerable small-angle scattering which could not be attributed to incoherence on the basis of known nuclear data. In transforming the measurements, it was assumed that all the scattering was coherent and that the formula of Debye[7] and of Zernicke and Prins[8] could be applied to the scattering pattern.

We have measured the scattering from liquid argon with higher statistical accuracy at 84°K, using 1.04 A neutrons, and have shown that the small-angle scattering is real and can be attributed to isotope incoherence arising from a large scattering cross section for A^{36}. The measured scattering pattern has been transformed by using the formula of Debye and of Zernicke and Prins, modified to allow for the incoherence. The radial distribution function which was calculated out to 20.0 A is an oscillating function whose amplitude decreases monotomically with increasing r. The positions of the first density maximum and the point where the atomic density rises from zero are discussed in relation to some two-particle potentials for argon.

APPARATUS

The measurements of the angular distribution of scattered neutrons were made by using one of the Chalk River neutron spectrometers with the arm recording in the antiparallel rocking position and with the NaCl monochromating crystal set to diffract neutrons of wavelength 1.04 A. The liquid argon was held in the 5 in. diameter cassette previously described.[6] The scattered intensities were measured at 84°K over the

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