$M1$ transitions, first observed by Bell and Graham,[11] and subsequently by many others. The radiative lifetime of the 59-keV state, using a conversion coefficient of 3.8 as extrapolated from the table of Rose,[12] was found to be 8.6 ± 1.0 nsec. This is longer by a factor of 67 ± 14 than predicted by the Weisskopf estimate for an allowed $M1$ transition of this energy. This delay is comparable in magnitude to the retardation observed for other l-forbidden magnetic dipole transitions in odd-Z nuclei shown in Table I.[13–15] In addition, it is in good agreement with the retardation of about 110 predicted by Sorensen[16] who, with Kisslinger,[17] has calculated wave functions for the states involved on the basis of a single-particle model with residual pairing and quadrupole forces. This indicates that the existence of l-forbidden $M1$ transitions is due, in part at least, to a collective nuclear interaction. Sorensen's results differ considerably, however, from many of the observed lifetimes; for instance, in Sb and Cs, indicating that some other effects are slao involved.

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Resonance Fluorescence in Ir^{191}†

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Resonance fluorescence from Ir^{191} has been investigated with Pt^{191} as the source of the exciting radiation. The centrifuge technique was used for the compensation of the recoil energy losses. The known level at 539 keV was excited and a mean lifetime of $(1.1_{-0.3}^{+0.7})\times10^{-11}$ sec was determined. A second level excited at (590 ± 15) keV might be identical with that suggested at 584 keV. The limits for the mean lifetime τ are $5\times10^{-13}<\tau<1.5\times10^{-11}$ sec. No resonance fluorescence was observed from the 625-keV level. The small transition probabilities for the γ transitions from the 539- and the 625-keV levels to the ground-state band are not compatible with the previous assignment to Nilsson orbit $(402)\uparrow$. A satisfactory agreement with the Nilsson model was obtained by assuming that these levels belong to the rotational band built on Nilsson state $(411)\uparrow$.

INTRODUCTION

IN the course of a systematic search for resonance fluorescence from odd nuclei in the transition region around mass number 190, the nucleus Ir^{191} has been investigated using the centrifuge technique. A radioactive Pt^{191} source supplied the exciting radiation. The interest was focused on the excitation of the levels at 539 and 625 keV in Ir^{191}. Much information about the properties of these levels is available from recent studies of the radioactive decay of Pt^{191}.[1–3] According to an interpretation in terms of the Nilsson model by Harmatz *et al.*,[1] both levels belong to the rotational band with the asymptotic quantum number $(402)\uparrow$. The ground state of Ir^{191} was assigned to Nilsson state $(402)\downarrow$. Resonance fluorescence experiments in Re^{187} [4] showed that the $(402)\downarrow-(402)\uparrow$ spin-flip transition has a high transition probability. On this basis the 539- and the 625-keV ground-state transitions in Ir^{191} were expected to be very fast. On the other hand, this is in contradiction to the observation of many low-energy γ transitions competing with these ground-state transitions.

EXPERIMENTS AND RESULTS

The experimental procedure and the apparatus for the observation of nuclear resonance scattering using the centrifuge technique has been described elsewhere.[5] A Pt^{191} source was obtained by irradiation of platinum enriched to 0.75% in Pt^{190} in the Oak Ridge research reactor. With a flux of about 2×10^{14} slow neutrons/sec cm^2 and an irradiation time of 3 days, 12 mg of Pt

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yielded about 2×10^8 539-keV γ quanta/sec. The source was transferred into a small aluminum capsule which fitted into the hole of the rotor. The scatterer, 3.66 g/cm^2 of iridium, was placed at a distance of about 8.5 in. from the source. For the determination of the background the iridium was replaced by a comparison scatterer of rhenium. The scatterers were matched by observing the scattering of the radiation emitted from the source at zero speed. Therefore any difference in scattering from a moving source must be attributed to resonance fluorescence. The radiation scattered under 125° was detected by a 3 in.$\times$3 in. NaI counter which was shielded by 1.84 g/cm^2 of lead to suppress low-energy radiation.

Measurements were performed at six different source velocities. For each velocity the background spectrum obtained with the rhenium scatterer was subtracted from the spectrum with the iridium scatterer. The points in Fig. 1 represent the remaining pulse-height distribution in the measurement at a source speed of 1050 m/sec. Two γ lines from resonance fluorescence at about 540 and 590 keV are apparent. Besides, the points at lower energies also indicate resonantly scattered radiation. Within the statistical errors, no resonance scattering was observed at 625 keV. The solid curve in the region above 500 keV is the result of the analysis using standard line shapes. The best fit to the experimental points was obtained by assuming γ lines at (540$\pm$10) and (590$\pm$15) keV.

The 539-keV level in Ir^{191} has a great variety of de-excitation modes. Therefore, if this level has been excited, a complex resonance spectrum containing γ transitions with 539, 457, 410, 360, and 353 keV and several transitions with lower energy is expected. The branching ratios for these γ transitions were obtained from studies of the radioactive decay of Pt^{191}. After correction for the efficiency of the detector the expected spectrum was constructed. The solid curve in Fig. 1 was extended to lower energies according to this estimated pattern. Except for a small surplus around 450 keV all low-energy resonance counts can be explained by assuming the excitation of the 539-keV level.

In order to determine the intensity of the incident radiation a direct spectrum of the source was measured with the same NaI counter in a distance of about 10 ft. In Fig. 1, the dashed curve indicates the incident spectrum where it differed from the scattered spectrum after normalization of the 540-keV lines to equal intensity. The 590-keV transition in the exciting radiation is completely masked by the intense 539- and 625-keV transitions.

The observed resonance effect versus the source velocity has been plotted in Fig. 2. The solid curves represent the theoretical speed dependence of the cross section for resonance fluorescence. The only parameters, the height of the maxima, were adjusted to give the best fit to the experimental points. The curves were computed by assuming that levels at 540 and 590 keV

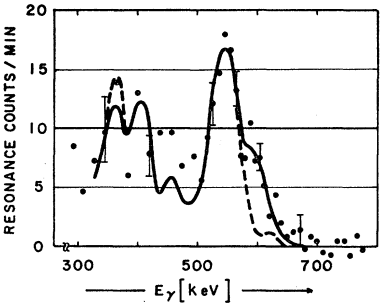

FIG. 1. Spectrum of the resonantly scattered radiation obtained with a source velocity of 1050 m/sec. The points refer to the experimental results. The solid curve above 500 keV represents the best fit to the data assuming the excitation of levels at 590 and 540 keV. The curve was extended to lower energies according to the complex γ spectrum expected from the de-excitation of the 539-keV level. The dashed curve indicates the spectrum of the exciting radiation. The curves are normalized to equal areas under the 540-keV photoline.

had been excited and that the width of the incident γ lines was caused entirely by the thermal motion of the emitting nuclei in the host lattice. The correction for the geometrical resolution of the apparatus shifts the maxima of the excitation functions from the theoretical values of 909 and 992 m/sec to 955 and 1040 m/sec. The agreement between expected and experimental resonance effect proves the excitation of levels at 540 and 590 keV. In order to estimate how accurately the position of a level can be determined from these excitation functions, the dashed curve in Fig. 2 was computed assuming the excitation of the 625-keV level. The height of the maximum was obtained from a least-square fit to the 590-keV data. As Fig. 2 shows, the experimental results are represented far better by the 590-keV excitation curve.

The assumption of a pure Maxwellian distribution for the shapes of the incident γ lines has to be modified if the recoil of the nucleus from the preceding K capture has not been dissipated completely when the γ decay

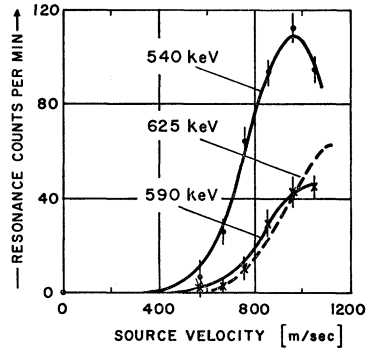

FIG. 2. Resonance effect versus source velocity. The points refer to the intensity of the 540-keV radiation, the crosses to the intensity of the 590-keV radiation resonantly scattered from iridium. The solid curves show the theoretical speed dependence of the cross section for the excitation of levels at 540 and 590 keV. The dashed curve represents the speed dependence expected for the excitation of the 625-keV level.

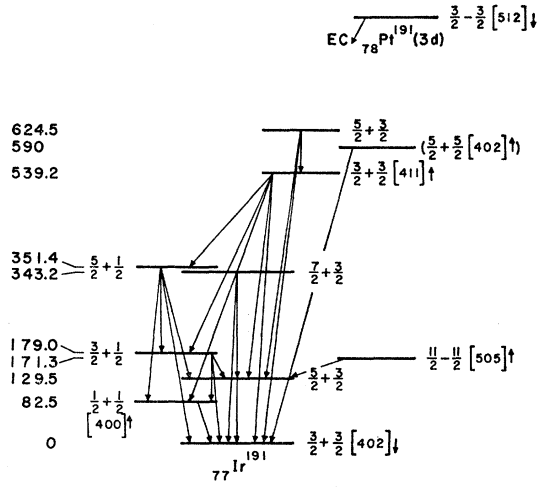

FIG. 3. Decay scheme of Pt^{191}. The spin, parity, and K quantum numbers are shown for each level. The lowest level of each rotational band is designated by the asymptotic quantum numbers $Nn_z\Lambda$ of the assigned Nilsson intrinsic state.

occurs. Since no distortion of the excitation functions has been found, the lifetimes of the levels must be longer than the time required to slow down the recoiling nuclei. With the information about the "slowing down" time obtained from the resonance fluorescence investigation[4] of the 773-keV level in Re^{187}, lower limits for the mean lifetimes of the 540- and the 590-keV level of $\tau > 5\times10^{-13}$ sec may be estimated, if these levels are populated directly by the K capture and not by a γ decay from an intermediate level.

The cross section σ for resonance fluorescence from Ir^{191} was calculated from the observed resonance effect and from the intensity of the incident radiation. For complete overlap of emission and absorption line, values of $\sigma_{539\text{ keV}}=1.32\times10^{-25}$ cm^2 and $\sigma_{590\text{ keV}}=0.53\times10^{-25}$ $(I_{539\text{ keV}}/I_{590\text{ keV}})$cm^2 were obtained. Since the 590-keV line was not resolved in the incident spectrum, the cross section for the 590-keV level contains the still unknown intensity ratio $I_{539\text{ keV}}/I_{590\text{ keV}}$ of the 539- and 590-keV transitions in the radioactive decay of Pt^{191}. The comparison of the experimental cross sections for resonance fluorescence with the corresponding theoretical expressions[6] yields

$$(g_2\Gamma_0^2/g_1\Gamma)_{539\text{ keV}}=(7.5\pm0.6)\times10^{-6}\text{ eV},$$

$$(g_2\Gamma_0^2/g_1\Gamma)_{590\text{ keV}}=(3.9\pm0.5)\times10^{-6}(I_{539\text{ keV}}/I_{590\text{ keV}})\text{eV},$$

and as upper limit for the 625-keV transition

$$(g_2\Gamma_0^2/g_1\Gamma)_{625\text{ keV}}<1.5\times10^{-5}\text{ eV}.$$

Γ_0 represents the partial width of the level for the ground state γ transition, and Γ the total width. g_2 and g_1 are the statistical factors of excited and ground state. In order to estimate $(\Gamma_0/\Gamma)_{539\text{ keV}}$ and $(\Gamma_0/\Gamma)_{625\text{ keV}}$, the relative γ intensities in the decay of Pt^{191} were determined by analyzing the spectrum of the incident radiation obtained with the 3-in.×3-in. crystal. The result of $I_{625\text{ keV}}:I_{539\text{ keV}}:I_{457\text{ keV}}:I_{410\text{ keV}}=0.11:1.00:0.25:0.54$ is in general consistent with corresponding data of Smith *et al.*[7] and Kalyan-Masih,[3] while the data of Harmatz *et al.*,[1] derived from conversion-electron spectra by multiplying with theoretical conversion coefficients, differ considerably. However, complete agreement with the present results can be achieved if the multipolarities of the 457- and 625-keV transitions are assumed to be $M1$ instead of $E2$. This change is also implied by the K/L intensity ratio of the conversion electrons.[1,8] Values of $(\Gamma_0/\Gamma)_{539\text{ keV}}=(0.35_{-0.05}{}^{+0.10})$ and $(\Gamma_0/\Gamma)_{625\text{ keV}}=0.43$ were calculated from the revised photon intensities of Harmatz *et al.* Assuming spin $\frac{3}{2}$ for the 539-keV level and spin $\frac{5}{2}$ for the 625-keV level the results of the resonance fluorescence experiment yield for the mean lifetimes

$$\tau_{539\text{ keV}}=(1.1_{-0.3}{}^{+0.7})\times10^{-11}\text{ sec},$$

$$\tau_{625\text{ keV}}>1.2\times10^{-11}\text{ sec}.$$

Evidence for several different γ transitions in Ir^{191} around 590 keV has been obtained from the observation of conversion electrons.[1,2,9] Two levels at 571 and 584 keV have been suggested.[10] The 584-keV level might be identical with the 590-keV level from the present investigation. A study of the γ spectrum from the decay of Pt^{191} with a high-resolution solid-state counter would be very useful to provide further information. The analysis of the incident γ spectrum measured with the NaI detector leads to $I_{539\text{ keV}}/I_{590\text{ keV}}>20$. Assuming a dipole or a quadrupole transition, it may be estimated that $g_2\Gamma_0/g_1\Gamma\leq2$. The limits for the lifetime of the 590-keV level become then 1.5×10^{-11} sec$>\tau_{590\text{ keV}}>5\times10^{-13}$ sec.

DISCUSSION

Figure 3 shows the level scheme of Ir^{191} as proposed by Harmatz *et al.*[1] The scheme was supplemented by the new 590-keV level established in the resonance fluorescence experiment. There is general agreement that a rotational band built on the ground state can be assigned to Nilsson state (402)↓, while a second band with the lowest level at 82.5 keV is very likely built on state (400)↑. The previous assignments of the 539- and

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TABLE I. $M1$ transition probabilities in Ir^{191}. The experimental information about the $M1$ transition probabilities T_{exp} (column 5) was obtained from the resonance fluorescence investigation and from lifetime measurements of the 129.5- and the 82.5-keV level. The assumed branching ratios $\Gamma_{\gamma M1}/\Gamma$ ($\Gamma_{\gamma M1}$ partial width for the $M1$ transitions, Γ total width) and spins are listed in columns 3 and 4. The results are compared with the transition probabilities expected from the Weisskopf formula and from the Nilsson model, T_{Wk} and $T_{Nilsson}$.

E_{level} (keV)	E_γ (keV)	$\Gamma_{\gamma M1}/\Gamma$	Assumed spins	T_{exp} 10^9 sec^{-1}	T_{Wk}/T_{exp}	Assignment	$T_{Nilsson}$ 10^9 sec^{-1}	$T_{Nilsson}/T_{exp}$
625	625	0.43	$\frac{5}{2}\rightarrow\frac{3}{2}$	<40	>110	(411)↑ − (402)↓	445	>11
	495	0.16	$\frac{5}{2}\rightarrow\frac{5}{2}$	<13	>180	− (402)↓	215	>16
	85	0.038	$\frac{5}{2}\rightarrow\frac{3}{2}$	< 3	> 4	− (411)↑	4.4	> 1.5
590	590					(402)↑ − (402)↓	5700	
539	539	0.35	$\frac{3}{2}\rightarrow\frac{3}{2}$	33	91	(411)↑ − (402)↓	640	19
	410	0.25	$\frac{3}{2}\rightarrow\frac{5}{2}$	23	57	− (402)↓	190	8
	457	0.09	$\frac{3}{2}\rightarrow\frac{1}{2}$	8.4	218	− (400)↑	40	5
	360	0.20	$\frac{3}{2}\rightarrow\frac{3}{2}$	19	47	− (400)↑	16	1
	188	0.012	$\frac{3}{2}\rightarrow\frac{5}{2}$	1.1	115	− (400)↑	0.6	0.5
129.5	129.5	0.23	$\frac{5}{2}\rightarrow\frac{3}{2}$	1.6[a]	26	(402)↓ − (402)↓	2.3	1
82.5	82.5	0.056	$\frac{1}{2}\rightarrow\frac{3}{2}$	0.010[b]	1000	(400)↓ − (402)↓	0.019	2

[a] Reference 13.
[b] Reference 14.

the 625-keV levels to Nilsson state (402)↑ were changed according to the discussion below.

Table I contains the available information about the $M1$ transition probabilities in Ir^{191}. According to the comparison with the Weisskopf estimate[11] (column 6) the transitions from the 539- and the 625-keV levels to the ground-state band are strongly hindered. This is in disagreement with the assignment of Nilsson orbit (402)↑ to these levels by Harmatz *et al.*[1] The multipolarities of the γ transitions favor spin $I=\frac{3}{2}$ for the 539-keV level which again is not compatible with the (402)↑ assignment.

On the other hand, since $K\leq I$, the 539-keV transition cannot be K forbidden. This leaves the Nilsson states (411)↑ and (411)↓ as possible assignments. The expected transition probabilities have been calculated for both cases using Nilsson's wave functions[12] for a nuclear deformation parameter $\eta=2$. Better agreement with the experimental data was obtained by assuming that the 539- and the 625-keV levels are members of the rotational band built on the Nilsson state (411)↑. The results of the calculation for this assumption are displayed in columns 8 and 9. The transitions from the (411)↑ to the (400)↑ states are fairly well described, while the (411)↑ − (402)↓ transitions are slower than predicted by at least a factor 10. The transition probability of the (400)↑ − (402)↓ transition is in very good agreement with the theory. The newly established 590-keV level could possibly be identified as the (402)↑ state expected in this energy region.

ACKNOWLEDGMENT

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