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Resonance Fluorescence in Re^{187}†

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The excited states of Re^{187}, populated in the decay of W^{187}, have been investigated by the resonance fluorescence method. Using the centrifuge technique, five resonantly scattered γ lines of 773-, 686-, 620-, 552-, and 479-keV energy, originating from the excitation of levels at 773, 686, and very probably 618 keV, have been observed. The measured angular distributions of these γ radiations are in agreement with spin assignments and multipole orders deduced from studies of the radioactive decay of W^{187}. Combining relative intensities given by Gallagher *et al.* with the observed cross sections for resonance scattering, the following mean lifetimes were computed: 773-keV level: $\tau=(2.5\pm0.3)\times10^{-13}$ sec, 686-keV level: $\tau=(8.5\pm0.7)\times10^{-12}$ sec, and 618-keV level: $\tau=(1.6\pm0.2)\times10^{-11}$ sec. These results agree with the theoretical interpretation in terms of the Nilsson model. The experiments give a lower limit of $\tau>1.0\times10^{-12}$ sec for the lifetime of the 864-keV level, assuming spin $\frac{3}{2}$ or $\frac{5}{2}$.

INTRODUCTION

THE low-lying excited states in Re^{187} populated in the decay of W^{187} have been investigated very extensively.[1–9] Several different decay schemes have been proposed.[1–6] In Fig. 1 the level scheme established by Gallagher, Edwards, and Manning[4] is reproduced. The original scheme is supplemented by the results from Coulomb excitation experiments.[10,11] Since the recent publications agree in the main features with this level scheme, it is adopted as a basis for further discussions.

The ground state and the 8 levels which are, according to Gallagher *et al.*, excited in the β decay from W^{187}, have been interpreted theoretically in terms of the Nilsson model.[12] The assigned quantum numbers are given in Fig. 1. The levels at 0, 206, 625, and 773 keV have been assigned to Nilsson intrinsic states 31, 32, 43, and 42, respectively, while the levels at 134, 301, and 618 keV can be understood as members of rotational bands build on the states 31 and 43. Although the levels at 512 and 686 keV show some properties of intrinsic Nilsson states, the branching ratios of divers γ transitions do not agree with this interpretation, so that these states have been explained as vibrational states with $K=-2$ coupled to the odd proton in Nilsson states 31 and 32, respectively. No definite assignment has been made to the 864-keV level.

The nucleus Re^{187}, with 75 protons and 112 neutrons, belongs to the upper limit of a deformed region, so that the strong coupling assumptions are somewhat uncertain. One sensitive test of the interpretation of the level scheme could be the measurement of transition probabilities for the different γ transitions. Lifetime measurements with the coincidence technique have so far been reported for the 134-keV level,[13] the 206-keV level,[14,15] and for the 686-keV level.[16] The lifetime for the

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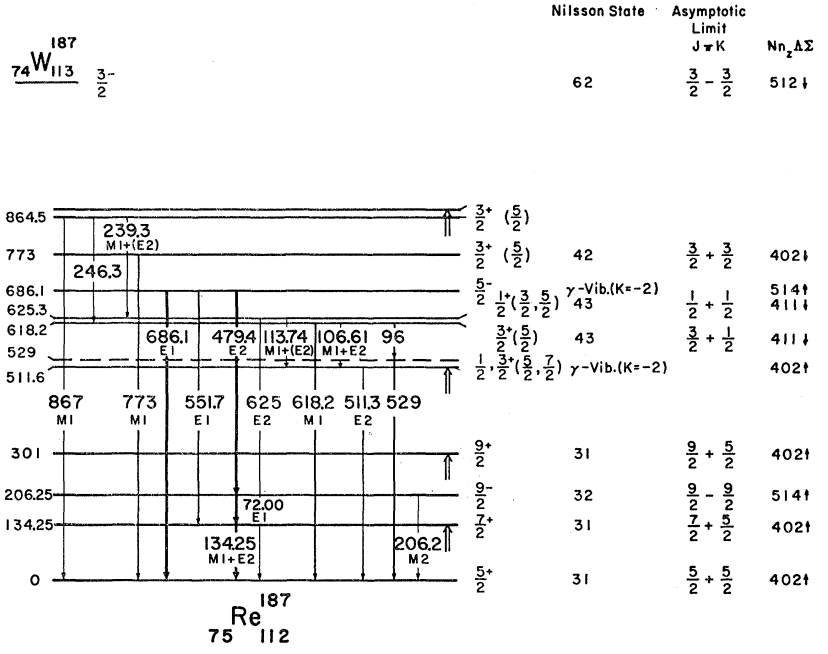

FIG. 1. Level scheme of Re^{187} as proposed and interpreted theoretically by Gallagher *et al.* (Ref. 4). The scheme is extended by some results of Coulomb excitation (Refs. 10 and 11) experiments.

134-keV level obtained with this technique agrees with results from the determination of the level width by Coulomb excitation[10] and Mössbauer effect.[17]

Since it can be expected from the Nilsson scheme that the higher excited levels ($\geq$512 keV) de-excite by rather fast ground-state transitions, Coulomb excitation, and resonance fluorescence measurements should be powerful techniques for the study of these transitions. Coulomb excitation of this energy region with α particles of about 20 MeV has been investigated by Nathan and Popov[11] studying α-γ coincidences. Two levels have been excited at 512 and 880 keV. Resonance fluorescence measurements have not been reported.

Improvement in the design of ultracentrifuges[18,19] and in the tensile strength of available rotor materials have brought these γ transitions within the range of a resonance fluorescence experiment using the centrifuge technique.[20] Such an experiment will be described and the conclusions drawn from the results will be discussed.

EXPERIMENTS

Scattering Experiments

To perform a resonance fluorescence experiment using the centrifuge technique, the velocities which are essential for the complete compensation of the γ recoil range from 882 m/sec for the 512-keV transition to 1491 m/sec for the 864-keV transition. With our "standard" type titanium alloy rotor, a speed of 1150 m/sec is within a reasonable safety range, allowing a source volume of about 10 mm^3. By reducing the size of the rotor tips, and consequently the effective source volume to about 1 mm^3, it was possible to increase the source speed by 15% to 1300 m/sec.[19] With this operating speed, an almost complete overlap of the 773-keV γ-ray emission and absorption line can be accomplished, and even for the 864-keV transition, 45% of the maximum possible effect is expected.

Since W^{187} sources with high specific activity are obtainable by irradiation of tungsten wire with a flux of more than 2×10^{14} neutrons/cm^2 sec in the Oak Ridge research reactor, the available source volume in the rotors did not restrict the source strength. For each run the rotor was loaded with 3–10 mg of irradiated tungsten wire with an initial activity of about 200 mCi.

A typical geometrical arrangement of rotor, scatterer, and detector is shown in Fig. 2. The 3×3-in. NaI-crystal detector was connected to a 400-channel analyzer. The analyzer was gated to accept pulses from the detector only when the source moved toward the scatterer. The gate was initiated by a light beam, reflected into a photomultiplier tube by a mirror mounted on the drive shaft of the centrifuge. After a rotation of the mirror through a fixed angle, the light beam produced a pulse in a second photomultiplier which was used to turn off the gate. The gate angle, during which the multichannel analyzer gate remained open, was varied for each experiment in order to optimize the experimental conditions concerning the counting rate of resonantly scattered γ quanta and the shielding of the detector crystal from the source.[18]

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The gated pulse-height distributions of the radiation scattered from a rhenium scatterer and an iridium comparison scatterer were measured as a function of speed and scattering angle. The two scatterers were matched for a γ energy of about 700 keV using a W^{187} source at rest at different positions on the rotor path. The difference in the two spectra at about 700 keV obtained with a moving source must be interpreted as due to resonance fluorescence. At lower energies the difference spectra had to be corrected slightly for mismatching of the scatterers.

Figure 3 shows a spectrum of the scattered radiation measured at a source speed of 1070 m/sec and a mean scattering angle of 140°. Five γ lines due to resonance fluorescence appear in the spectrum. The background determined with the Ir scatterer has already been subtracted; it varied from less than 1% under the peak at 773-keV energy to 50% at 479-keV energy. The dashed curve in Fig. 3 represents the spectrum of the incident radiation measured with the same 3×3-in. crystal at a distance of about 20 ft from the W^{187} source. A comparison of the two spectra permits the assignment of the five observed resonance lines to the 773-, 686-, (625+618)-, 552-, and 479-keV transitions in Re^{187}. The 625- and the 618-keV lines cannot be resolved with an NaI-crystal detector, but a careful energy calibration suggests 618 keV for the observed line. The fact that the intensity ratios in the scattered radiation differ considerably from the ratios in the incident radiation leads immediately to the conclusion that more than one level has been excited.

Resonance spectra were taken as function of the source speed between 0 and 1300 m/sec. The gate angle was 20°. The analysis of the experimental spectra was done by using normal line shapes obtained by placing weak sources of Mn^{54}, Cs^{137}, Na^{22}, and Be^{7} behind and in front of the scatterer.

In Fig. 4 the resonance effects for the 773-, the 686-, and the (625+618)-keV transitions are plotted versus the source speed. The difference in the excitation functions of these three γ transitions indicates that three different levels have been excited. The velocities v_0 which correspond to the maxima of these curves allow, after correction for a small velocity shift caused by the finite geometrical resolution of the experimental apparatus, the calculation of the energies E_{level} of the excited states, using the relation $v_0 = E_{\text{level}}/Mc$ (M = mass of a Re^{187} atom, c = velocity of light). A comparison between these level energies E_{level} and the energies of the γ quanta E_γ observed in the γ spectra proves unambiguously that the 773-, the 686-, and the

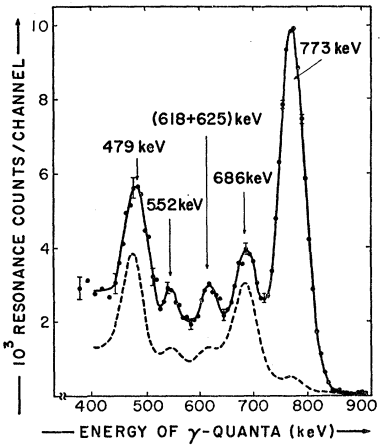

FIG. 3. The spectrum represents the pulse-height distribution of the scattered radiation emitted from the W^{187} source moving with a speed of 1090 m/sec toward the Re scatterer. The background, measured with an Ir scatterer, has already been subtracted. The mean scattering angle was 140°. The γ lines at 773, 686, (625+618), 552, and 479 keV are due to resonance fluorescence. The counts at 860 keV are due to pile-up effects. For comparison the dashed curve shows the distribution of the incident radiation measured with the same detector. The curves are normalized to equal areas under the 686-keV photoline.

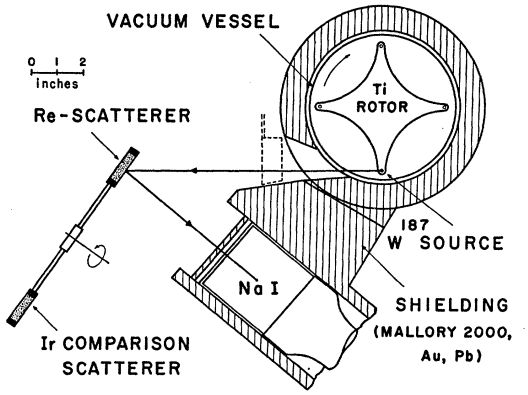

FIG. 2. Experimental arrangement for the resonance scattering experiment with the centrifuge technique. The NaI crystal, shielded by 3.8 g/cm² lead to suppress low-energy radiation, was connected to a 400-channel analyzer. The dashed lines indicate the position of the absorber in the self-absorption experiment.

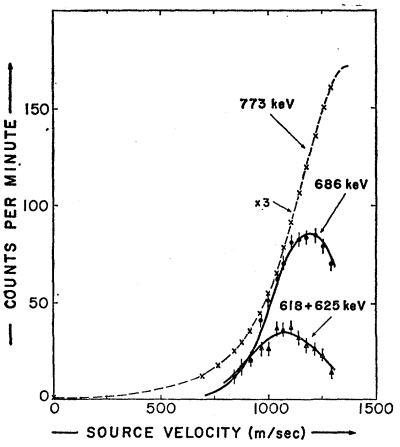

FIG. 4. Resonance effect as function of source velocity. The crosses refer to the 773 keV, points to the 686 keV and triangles to the (625+618)-keV line. The solid curves labeled "686 keV" and "(625+618) keV" represent the theoretical velocity dependence for the excitation of a 686- and a 620-keV level.

(625+618)-keV transitions are ground-state transitions. In Fig. 4 the excitation functions for the 552- and the 479-keV transitions are omitted since, within the experimental errors, the speed dependence is the same as for the 686-keV transition, indicating that these two transitions originate from the 686-keV level. Therefore, without further analysis, the existence of excited levels in Re^{187} at 773-, 686-, and 618- and/or 625-keV energy has been proved. This result confirms the level scheme proposed by Vergnes,[3] Gallagher *et al.*,[4] Arns *et al.*,[5] and Michaelis,[6] and is in disagreement with former decay schemes.[1,2]

No resonance effect could be seen at 864- and 512-keV energy; in spite of the fact that in a special search for a resonance effect of the 864-keV γ ray, the rotor was run for several hours at a source speed of 1290 m/sec. To avoid pile-up effects between resonantly scattered γ quanta of 773-keV and low-energy background radiation, the face of the 3×3-in. NaI detector was shielded by 7.5-g/cm^2 lead plus 1.2-g/cm^2 tin.

In order to deduce the experimental cross section for resonance fluorescence for the 686-keV transition from the observed resonance effect, the 686-keV intensity in the exciting radiation has been obtained by analyzing the pulse-height distribution of the incident radiation. The intensities for the calculation of the cross sections of the other γ transitions could be obtained with more accuracy by multiplying the 686-keV intensity by the intensity ratios quoted by Gallagher *et al.*,[4] and correcting for the efficiency of the detector rather than by an analysis of the pulse-height distribution of the incident radiation.

The level widths of the excited states can be obtained by comparing these experimental results with the theoretical cross sections. As long as the total lifetime of an excited state is long enough so that the recoil of the preceding β and/or γ decay is completely slowed down before it decays, the cross section σ_{av} for resonance fluorescence is given by[21]

$$\sigma_{av}=\frac{g_2c^2h^2\Gamma_0^2}{g_1 4\pi^{1/2}E_\gamma^3\Gamma}\left[\frac{Mc^2}{2k(T_1+T_2)}\right]^{1/2}\times\exp-\left[\frac{M(E_\gamma/Mc-u)^2}{2k(T_1+T_2)}\right], \quad (1)$$

where g_2 and g_1 are the statistical weights of excited and ground states, c is the velocity of light, h is Planck's constant, E_γ is the energy of the excited level, M is the mass of the recoiling nucleus, and u is the relative speed of source and absorber. Γ_0 represents the partial width of the level for the ground-state transition, Γ the total-level width, and k the Boltzmann constant. T_1 and T_2 are the effective temperatures of source and scatterer obtained from the actual temperatures by taking into account the effect of the binding[21,22] in the source and the scatterer material. An effective temperature of 335°K for the source and 312°K for the absorber has been assumed.

In Fig. 4 the solid curves labeled "686 keV" and "(625+618) keV" represent the theoretical cross sections which give the best fit to the experimental data assuming the validity of Eq. (1). The only adjustable parameter, $g_2\Gamma_0^2/g_1\Gamma$, was determined to be $g_2\Gamma_0^2/g_1\Gamma=(1.82\pm0.16)\times10^{-5}$ eV for the 686-keV transition. Since the 625- and the 618-keV lines are unresolved, the parameter in this case is

$$(g_2\Gamma_0^2/g_1\Gamma)_{618\text{ keV}}+0.165(g_2\Gamma_0^2/g_1\Gamma)_{625\text{ keV}}=(2.5\pm0.3)\times10^{-5}\text{ eV}.$$

From Fig. 4 it can be easily seen that the excitation function for the 773-keV level does not have the Gaussian shape expressed by (1), indicating that the lifetime of this level must be very short, so that the recoil of the preceding β decay has an appreciable effect on the shape of the emitted line. Since it was possible to measure the excitation function nearly up to the maximum of the effect, the experimental data have been analyzed by computing $\int_{-\infty}^{+\infty}\sigma_{av}(u)du$, which is independent of the influence of the preceding radiations. A comparison with the theoretical value from integration of Eq. (1) gives for the parameter $g_2\Gamma_0^2/g_1\Gamma=(1.75\pm0.22)\times10^{-3}$ eV. This result has been corrected slightly, taking into account the self-absorption in the scatterer.

Angular Distribution Measurements

To obtain more information about the character of the γ transitions, the angular distributions of the resonantly scattered radiations were investigated. The measurement was performed at scattering angles of 115°, 130°, and 140° at a rotor speed of 1070 m/sec. At this speed the ratios of the yields of the 686- and of the (625+618)-keV radiation to the 773-keV resonantly scattered radiation are very close to their maxima. The results were analyzed in terms of an angular distribution $W(\theta)=1+A_2P_2(\cos\theta)$ with $P_2(\cos\theta)$ the second Legendre polynomial. The experimental anisotropy coefficients A_2 are listed in Table I. Since no big anisotropy occurred and the strong 773-keV line made the analysis of the low-energy part of the spectra rather uncertain, the relative errors are big.

Self-Absorption Experiment

The peak value of the cross section for resonance scattering of the 773-keV radiation was about 7 b per Re^{187} atom. Since this value is comparable with the electronic attenuation cross section for γ quanta of 773 keV, which is 25 b in natural rhenium, a self-absorption experiment was possible. This type of experi-

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TABLE I. Summary of the experimental results. From the results of the resonance fluorescence experiments listed in columns 2 and 3, the data in columns 6 and 8 have been calculated using spins, multipole orders, and branching ratios given by Gallagher *et al.* (Ref. 4) and reproduced in columns 4, 5, and 7.

E_γ (keV)	Angular distribution $A2$	$g_2\Gamma_0^2/g_1\Gamma$ (eV)	Assumed spins	Multipole order	Mixing amplitude δ	Γ_0/Γ	τ_{level} (sec)
864.5	...	$<1.3\times10^{-4}$	$\frac{5}{2}^+,\frac{3}{2}^+\rightarrow\frac{5}{2}^+$	$M1$		0.54	$>1.0\times10^{-12}$
773	$+(0.03\pm0.05)$	$(1.75\pm0.22)\times10^{-3}$	$\frac{3}{2}^+\rightarrow\frac{5}{2}^+$	>85% $M1$ <15% $E2$	$-0.40<\delta<0.15$	1	$(2.5\pm0.3)\times10^{-13}$
686.1	$+(0.21\pm0.10)$	$(1.82\pm0.16)\times10^{-5}$	$\frac{5}{2}^-\rightarrow\frac{5}{2}^+$	$E1$	$-0.10<\delta<0.15$	0.49	$(8.5\pm0.7)\times10^{-12}$
551.7	<0	...	$\frac{5}{2}^-\rightarrow\frac{7}{2}^+$	$E1$ <1% $M2$			
479.4	$-(0.10\pm0.24)$	...	$\frac{5}{2}^-\rightarrow\frac{9}{2}^-$	$E2$			
625.3	$-(0.17\pm0.25)$	$(2.5\pm0.3)\times10^{-5}$	$\frac{1}{2}^+\rightarrow\frac{5}{2}^+$	$E2$		0.82	
618.2			$\frac{3}{2}^+\rightarrow\frac{5}{2}^+$	>85% $M1$	$-0.40<\delta<0.15$	0.96	$(1.6\pm0.2)\times10^{-11}$
511.3	...	$<4\times10^{-5}$	$\frac{1}{2}^+\rightarrow\frac{5}{2}^+$	>99% $E2$		1	$>6\times10^{-12}$

ment has certain advantages over the normal scattering experiment, since the results are independent of the absolute intensity and of the line shape $N(E)dE$ of the incident γ radiation, as long as $N(E)dE$ is a slowly varying function of $N(E)(dN/dE=\text{const})$.[21] Furthermore, the absorption cross section is a function of Γ_0 alone, so that a combination of scattering and absorption measurement allows the determination of Γ_0/Γ, the branching ratio between the ground-state transition and other modes of de-excitation.

For the self-absorption experiment, a rhenium absorber of 4.4-g/cm^2 thickness was placed between the rotor and the scatterer as indicated by the dashed lines in Fig. 2. The rhenium absorber could be replaced by a tungsten absorber of the same electronic attenuation. The matching of the absorbers was checked in a good geometry with radioactive sources of Mn^{54} and Cs^{137}.

In the actual experiment, spectra were taken for the possible four combinations of scatterers and absorbers with the procedure used in the scattering experiment. The source speed 1215 m/sec was rather close to the maximum of the excitation function of the 773-keV line.

To compute the absorption effect, the spectrum N_{ReRe} measured with a rhenium absorber and a rhenium scatterer was subtracted from the spectrum N_{WRe} obtained with a tungsten absorber and a rhenium scatterer. Since the detector was not shielded sufficiently from the absorber, γ quanta resonantly scattered in the rhenium absorber could reach the detector. The result was corrected for this effect by subtracting the difference N_{WIr} (measurement with tungsten absorber and iridium comparison scatterer) minus N_{ReIr} (measurement with rhenium absorber and iridium scatterer). In the final spectrum, $N_{\text{final}}=(N_{\text{WRe}}-N_{\text{ReRe}})-(N_{\text{WIr}}-N_{\text{ReIr}})$, only one peak corresponding to 773-keV energy remained. This indicates that, of the five γ lines seen in the scattering experiment, the cross section for resonance absorption is comparable with the electronic cross section only for the 773-keV transition. Integration over this absorption line gave for the ratio

$$R(773)=N_{\text{final}}/(N_{\text{WRe}}-N_{\text{WIr}})=(13.4\pm1.7)\%.$$

R is given by[21]

$$R=1-\frac{\int_{-\infty}^{+\infty}\sigma_{\text{sc}}(E)N(E)\exp-[(\sigma_{\text{el}}+\sigma_{\text{abs}}(E))nx]dE}{\int_{-\infty}^{+\infty}\sigma_{\text{sc}}(E)N(E)\exp-(\sigma_{\text{el}}nx)dE}.$$

$\sigma_{\text{sc}}(E)$ represents the energy dependence of resonance scattering in the scatterer. σ_{abs} is the cross section for resonance absorption, σ_{el} is the cross section for electronic attenuation in the absorber, n is the number of nuclei per cm^3, x is the absorber thickness, and $N(E)$ is the energy distribution of the exciting radiation.

This integral is independent of $N(E)$, if $N(E)$ is a slowly varying function of E. In a self-absorption experiment with an exciting radiation from a radioactive decay, this condition is usually not fulfilled. In order to calculate the cross section σ_{abs} from the experimental ratio R, the shape of the emission line was assumed to be Gaussian $N=N_0\exp-[(E-E_0)/\Delta_{\text{eff}}]^2$. The effective width Δ_{eff} was estimated from the results of the scattering experiment. The value obtained for σ_{abs} differed only by 5% from a calculation with a constant $N(E)$ so that even for this type of self-absorption experiment, the exact knowledge of the shape of the emission line is not essential. The final result of the self-absorption experiment gives $g_2\Gamma_0/g_1=(1.67\pm0.24)\times10^{-3}$ eV for the 773-keV transition. This value is in agreement with the scattering data, confirming the assumptions made about Γ_0/Γ in the evaluation of the scattering experiment (see Table I) and the intensity ratio I_{773}/I_{686} in the radiation from the W^{187} decay.

DISCUSSION

The results of the resonance fluorescence experiments are summarized in Table I. Some remarks about the

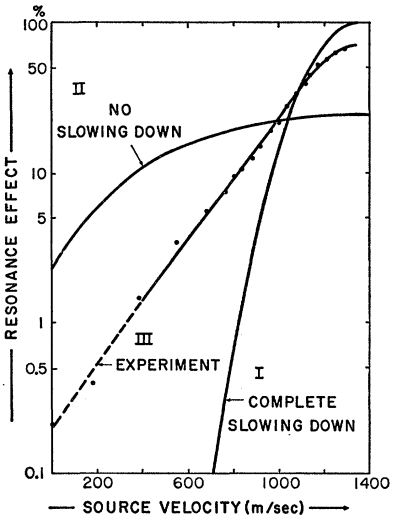

FIG. 5. Resonance effect versus source velocity for the 773-keV transition. Curve I represents the effect expected without any influence from the recoil of the preceding β decay (formula 1). Curve (II) is calculated assuming no slowing down of the nuclei between β and γ decay. These curves and also the experimental curve III are normalized that the cross sections for resonance fluorescence integrated over the velocity are equal.

assumptions and conclusions will be given for each level.

773-keV level. Conversion coefficient measurements[4,8] showed that this transition is a pure $M1$-transition with less than 15% $E2$ admixture.[4] On this basis, combined with branching considerations, the spin of the 773-keV level has been assigned as $\frac{3}{2}$, or less likely, $\frac{5}{2}$. The almost isotropic distribution of the resonantly scattered 773-keV radiation gives for the mixing amplitude $\delta_{E2/M1}=(I_{E2}/I_{M1})^{1/2}$ a value $-0.40<\delta<+0.15$, assuming spin $\frac{3}{2}$, or $-0.75<\delta<+0.15$ assuming $\frac{5}{2}$. Both values are consistent with the conversion data. Using the spin assignment $\frac{3}{2}$ and $\Gamma_0/\Gamma=1$, the total lifetime of the 773-keV level has been calculated from the resonance fluorescence experiment. The result is $\tau_{773}=(2.5\pm0.3)\times10^{-13}$ sec.

Having determined the lifetime of the level, the experimental velocity dependence of the resonance effect can be compared with theoretical predictions for different assumptions of the "slowing down" time of the recoiling rhenium nuclei in the tungsten source. This is done in Fig. 5 for two extreme cases. Curve I represents the velocity dependence expected if the recoil of the preceding β decay is completely slowed down before the γ decay occurs. Curve II is calculated assuming no slowing down of the recoil from the β decay before the γ decay occurs. To simplify the calculation, no β-neutrino correlation has been taken into account. A comparison with the experimental curve III at low source velocities allows an estimate of the "slowing down" time. The result of about 2.5×10^{-14} sec for Re nuclei with velocities of the order of 10^5 cm/sec in a W lattice is in agreement with similar measurements for other nuclei by Ofer and Schwartzschild.[23] The mean free path length of the Re nuclei is then about 0.3 Å.

686-keV level. From decay scheme studies spin $\frac{5}{2}$ and negative parity of this level are well established. The character of the 686-keV transition is, according to conversion measurements,[4,8] pure $E1$. The angular distribution of the resonantly scattered 686-keV radiation is consistent with these results, in that a mixing amplitude of $-0.10<\delta_{M2/E1}<0.15$ is obtained. The experimental anisotropy coefficient $A_2=-(0.10\pm0.24)$ of the 479-keV transition following the excitation of the 686-keV level agrees with the value of $A_2=+0.08$, which is expected for a $\frac{5}{2}(1)\frac{5}{2}(2)\frac{9}{2}$ cascade.

Using the experimental branching ratios[4] and spin $\frac{5}{2}$, the total lifetime of the 686-keV level is evaluated from the determined quantity $g_2\Gamma_0^2/g_1\Gamma$. The result, $\tau_{686}=(8.5\pm0.7)\times10^{-12}$ sec, disagrees by a factor 30 with the lifetime of the 686-keV level observed with the β-γ-coincidence technique by Vartapetyan.[16] No explanation seems to be apparent. An obvious suggestion would be that the two experiments are concerned with two different levels at 686 keV. However, since the initial intensity ratios between the 686-, the 552-, and the 479-keV γ radiations are reproduced in the radiation resonantly scattered from the 686-keV level, it is extremely unlikely that a level different from the level investigated by Vartapetyan has been excited. Furthermore, if the 686-keV radiation from the W^{187} decay consists of two different energies, the intensity of the 686-keV radiation leading to the excitation of the level would have to be much lower than the intensity of the radiation investigated by Vartapetyan. Therefore, under this assumption a revised computation of the result of the resonance scattering experiment would lead to a very short lifetime, which is in contradiction to the absence of any self-absorption effect on the 686-keV radiation.

(625+618)-keV levels. The uncertainty in the angular distribution measurement does not permit a decision as to whether the 625-keV or the 618-keV level has been excited. Since A_2 is always positive for the angular distribution of a ground-state transition, the experimental result indicates a nearly isotropic distribution. This is consistent with spin assignment $\frac{3}{2}$ and $-0.40<\delta_{E2/M1}<+0.15$ for the 618-keV level,[4] but also with spin $\frac{1}{2}$ for the 625-keV level. Adopting these spin assignments, and the branching ratios from Ref. 4, the experimentally determined quantity

$$(g_2\Gamma_0^2/g_1\Gamma)_{618\text{ keV}}+0.165(g_2\Gamma_0^2/g_1\Gamma)_{625\text{ keV}}$$

simplifies to

$$\Gamma_{0\ 618\text{ keV}}+0.070\Gamma_{0\ 625\text{ keV}}=3.85\times10^{-5}\text{ eV}.$$

Assuming $\Gamma_{0\ 618\text{ keV}}\sim0.07\Gamma_{0\ 625\text{ keV}}$ would lead to an un-

[23] S. Ofer and A. Schwarzschild, Phys. Rev. Letters **3**, 385 (1959).

TABLE II. Summary of the known transition probabilities in Re^{187}. The experimental results T_{exp} are compared with theoretical predictions: $T_{Weisskopf}$ calculated with the Weisskopf formula omitting spin factors and $T_{Nilsson}$ calculated using Nilsson wave functions.

	Assumed		T_{exp} (sec^{-1})			Nilsson Model		
E_γ (keV)	Spins	Multipole order	This experiment	Others	$\frac{T_{exp}}{T_{Weisskopf}}$	Assumed states	$T_{Nilsson}$	$\frac{T_{exp}}{T_{Nilsson}}$
134.3	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	$M1$	...	2.4×10^{10}[a]	1/2	31 rot $\rightarrow$ 31	2.8×10^{10}	1
		$E2$	...	7.1×10^{8}[a]	200	31 rot $\rightarrow$ 31	7.0×10^{8}	1
206.3	$\frac{9}{2}^- \rightarrow \frac{5}{2}^+$	$M2$	...	6.0×10^{3}[b]	1/88	32 $\rightarrow$ 31	1.2×10^{4}	1/2
72.0	$\frac{9}{2}^- \rightarrow \frac{7}{2}^+$	$E1$	...	6.1×10^{5}[b]	$1/2\times10^{-6}$	K forbidden	0	f
618.2	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	$M1$	5.9×10^{10}		1/80	K forbidden	0	f
106.6	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	$M1+(E2)$	3.9×10^{8}		1/70	43 $\rightarrow \gamma$ vibr.	0	f
625.3	$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+$	$E2$	...		...	43 $\rightarrow$ 31	4.3×10^{7}	...
113.7	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$	$M1+(E2)$	...		...	43 $\rightarrow \gamma$ vibr.	0	...
773	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	$M1$	4.0×10^{12}		1/2	42 $\rightarrow$ 31	2.0×10^{13}	1/5
		$E2$	$<8\times10^{11}$			42 $\rightarrow$ 31	5.2×10^{7}	...
864.5	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	$M1+(E2)$	$<5.5\times10^{11}$		$<1/23$	33 $\rightarrow$ 31	8.1×10^{12}	$<1/15$
	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$	$M1+(E2)$	$<2.5\times10^{11}$[c]		$<1/50$	27 $\rightarrow$ 31	1.4×10^{12}	$<1/5$
246.3	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$M1+(E2)$	$<1.9\times10^{11}$			33 $\rightarrow$ 43 rot	2.0×10^{11}	...
239.3	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	$M1+(E2)$	$<1.2\times10^{11}$			33 $\rightarrow$ 43	2.2×10^{11}	...
880	$\rightarrow \frac{5}{2}^+$	$E2$		3×10^{11}[d]		...	...	...
686.1	$\frac{5}{2}^- \rightarrow \frac{5}{2}^+$	$E1$	5.7×10^{10}[e]		$1/2\times10^{-4}$	36 $\rightarrow$ 31	1.8×10^{10}	(3)
551.7	$\frac{5}{2}^- \rightarrow \frac{7}{2}^+$	$E1$	1.0×10^{10}[e]		$1/6\times10^{-4}$	36 $\rightarrow$ 31 rot	3.6×10^{9}	(3)
479.4	$\frac{5}{2}^- \rightarrow \frac{9}{2}^-$	$E2$	4.9×10^{10}[e]		24	...	...	...
511.3	$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+$	$E2$		5.1×10^{10}	18	...	...	...

[a] Refs. 10, 13, and 17.
[b] Refs. 14 and 15.
[c] Computed with branching ratios of Ref. 6.
[d] Calculated from the result given in Ref. 11, assuming $g_1\Gamma_0/g_2\Gamma=1$.
[e] The result of Vartapetyan is about 1/30 of this value (see discussion).
[f] Comparison with column 6 shows that the experimental transition probabilities are small.

reasonably short lifetime for the pure $E2$ transition of 625 keV, with about 1/100 of the value estimated from the single-particle model. Since no evidence for an extremely fast 625-keV γ transition has been found in the Coulomb excitation experiment,[11] it seems to be reasonable to ascribe the resonance effect to the 618-keV $M1$ transition. Under this assumption the lifetime for the 618-keV level becomes $\tau_{618}=(1.6\pm0.2)\times10^{-11}$ sec.

Assumptions about the transition probability of the 625-keV transition are not essential if the somewhat revised decay scheme, published most recently by Michaelis,[6] is adopted. Based on the observation of coincidences between 625- and 134-keV γ quanta, the level at 625 keV was replaced by a level at 760 keV. Unless this new level were excited in the resonance fluorescence experiment, no radiation of 625 keV could be expected. An excitation of the 760-keV level, with following deexcitation over the 625–134-keV cascade, would have been observed in the excitation function of the (618+625)-keV level as a deviation from the predicted shape at high-source velocities.

864-keV level. The experimental information about this level is rather uncertain. Conversion measurements[4,8] propose for the character of the ground-state transition a rather pure $M1$ transition. Since the branching to the (625/618)-keV doublet makes spin $\frac{3}{2}$ the most likely spin assignment, an allowed and therefore fast $M1$ transition should be expected; however, the fact that the γ transitions of 246 and 239 keV compete with the 864-keV transition indicates a slow transition. The lack of any resonance effect gives an upper limit of 1.0×10^{-12} sec for the lifetime of this level, using the intensity results of Gallagher *et al.*[4] This lifetime is too long for an allowed $M1$ transition from a pure Nilsson-state with spin $\frac{3}{2}$. The revision of the decay scheme introduced by Michaelis,[6] permitting spin assignment $\frac{5}{2}$ for this level, would not influence the result for the upper limit of the total lifetime. The proposed Nilsson state 27 cannot be excluded on grounds that there is no resonance effect (see Table II).

From the result of the Coulomb excitation of a level at (880±20) keV,[11] a value of $g_2\Gamma_{E2}\Gamma_0/g_1\Gamma=2\times10^{-4}$ eV can be calculated (Γ_{E2} is the width for the $E2$ part of the ground-state transition). A comparison with the upper limit for the width of the 864-keV level obtained in the resonance fluorescence experiment (Table I) shows, independent of any spin and branching assumptions, that these levels are not identical. Even with a possible big error in the Coulomb excitation experiment, this argument is valid as long as the character of the 864-keV transition is predominately $M1$. An indication that also two levels in this energy region are fed by the W^{187} decay has been found in an investigation of the 864-keV radiation in a photoelectron spectrometer by Dzelepov *et al.*[24] It was reported that this line consists of a doublet having energies of (864±9) and (891±9) keV with about equal intensity. The possible existence of two levels might influence the results of the conversion coefficient measurement, and also the upper limit of the transition probability obtained from the resonance fluorescence experiment. Further investigation of this energy region seems to be essential before any conclusions can be drawn.

[24] B. S. Dzelepov, V. L. Rumyantsev, Yul. Kholnov, and G. E. Shchukin, Bull. Acad. Sci. USSR **24**, 299 (1960).

In Table II the experimental results are compared with theoretical predictions. In columns 4 and 5 all information about the transition probabilities of the major γ transitions occurring in Re^{187} is listed. In column 6 these experimental results are compared with the transition probabilities calculated from the Weisskopf formula,[25] omitting spin factors and using a nuclear radius of $R=1.2\times10^{-13}$ $A^{1/3}$ cm.

Predictions of the Nilsson model are compiled in column 8. From the magnetic moment and the quadrupole moment of the ground state of Re^{187} and from the mixing ratio of the 134-keV transition, a deformation parameter of about $\eta=3$ had been derived for the Re^{187} nucleus.[26,4] For $\eta=4$ the wave functions for the different Nilsson states assigned by Gallagher *et al.*[4] to the ground and excited states are calculated byNilsson.[12] Using these wave functions, and for Nilsson's quantity $\mu=0.45$, the transition probabilities listed in column 8 have been computed. The results are compared with the experiment in column 9.

The ground-state transitions from the 134-keV rotational level and also from the 206-keV level are rather well described by these wave functions. The K-forbidden 72-keV transition is very slow, as expected. The $M1$-transition from the 618-keV level, Nilsson state 43, to the ground state is also K forbidden. The experimental result shows a considerable retardation in comparison with the prediction of the Weisskopf formula which gives a rather good estimate for the two allowed $M1$ transitions in Re^{187}. Michaelis' proposal[6] of Nilsson state 33 for this level would lead to an allowed $M1$ transition, which is not consistent with the experimental result. From the assignment of spin $\frac{3}{2}$, state 42, to the 773-keV level, a fast $M1$ transition to the ground state is expected (in the asymptotic limit it is a spin flip transition), with a transition probability of 2.0×10^{13} sec^{-1}. A spin-$\frac{5}{2}$ assignment, e.g., state 27, would lead to a $M1$-transition which is at least 20 times slower. The big resonance effect is in favor of the first assignment even though the quantitative comparison shows an experimental transition probability which is too small. However, it should be noted that the Nilsson model and most of the other independent particle models generally predict $M1$-transition lifetimes which are shorter than the experimentally determined values.

The fast 512-keV $E2$ transition is consistent with an interpretation of the 512-keV level as a vibrational state coupled to the odd proton. The 107-keV transition to this level from the Nilsson state 43 should be forbidden; the experiment shows a somewhat retarded transition. More problematic seems to be the interpretation of the 686-keV level. The result of the resonance fluorescence experiment for the $E1$ transitions of 686- and 552-keV energy could be understood assuming Nilsson state 36 as a possible assignment,[4,16] but then the fast $E2$ transition of 479 keV cannot be explained, even with a small collective admixture to the Nilsson state. Unlike Vartepateyan's[16] interpretation of his results, this measurement favors strongly the interpretation of Gallagher *et al.*[4] that the 686-keV level is a vibrational state based on the Nilsson state 32. The ratios of the transition probabilities of the 512- and the 479-keV transition should be 1.4, in rough agreement with the experiment. A comparison with the vibrational transitions in the neighboring even-even nuclei, taking into account the different vector addition coefficients[27] shows that these transitions in Re^{187} are only somewhat faster. The 686-keV vibrational state must contain some impurities to permit the rather slow $E1$ transitions to the ground-state rotational band and the β decay from W^{187}. An even faster $E1$ transition from a well-established vibrational state to a pure Nilsson state has been observed in Ho^{165}.[28]

It might be noted that in the asymmetric rotor model,[29] extended for odd nuclei by Hecht and Satchler,[30] the observed vibrational states are interpreted as rotational states of an asymmetric rotor coupled to the $\frac{5}{2}^+$ and $\frac{9}{2}^-$ odd-nucleon states. In this model the $E1$ transitions from the 686-keV level are no longer completely forbidden as in the strict Nilsson model.

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