AN INVESTIGATION OF THE EXCITED STATES OF Re^{187}

M. V. KLIMENTOVSKAYA and P. I. SHAVRIN

Nuclear Physics Institute, Moscow State University

Submitted to JETP editor November 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 1360-1365 (May, 1959)

The excited-state angular momenta and multipole types of the γ transitions of Re^{187} have been determined by measuring the angular correlation of the $552 - 134$, $480 - 134$, and $72 - 134$ kev γ cascades. A value of $(2.2 \pm 0.5) \times 10^{-2}$ was obtained for the ratio of the E2 and M1 amplitudes of the radiation mixture $\delta^2 = I(E2)/I(M1)$, in the γ transition with an energy of 134 kev. The relative intensity of the 552-kev γ line was determined. The internal conversion coefficient for the K-shell γ transition with an energy of 134 kev was measured.

INTRODUCTION

THE decay of W^{187} and the nuclear level scheme of Re^{187} has been repeatedly investigated by various methods.[1-7] The results of these investigations, which characterize the properties of the β transitions of W^{187} and the γ transitions of Re^{187}, are illustrated by the table and by the decay scheme of W^{187} in Fig. 1.

One may assume that the sequence of γ transitions, spins and parities of the ground state and the first excited state, and also the multipole types of the γ_1 and γ_3 transitions of the Re^{187} nucleus have been safely established. The information on the multipole types of the other γ transitions is contradictory.

The present work had the purpose of obtaining additional data relative to the Re^{187} level scheme with the aid of scintillation coincidence methods.

APPARATUS

A block diagram of the measuring setup is shown in Fig. 2. The detection of the γ radiation was made by cylindrical crystals of NaI (Tl) of diameter 30 mm and heights 13 and 20 mm. The crystals were mounted on the photocathodes of two FEU-S photomultipliers. After amplification

γ-transition	Energy, kev	Relative intensity	Internal conversion coefficient	K/L	Multipolarity
γ_2	72.00±0.007 [1]				E1 [2]*, E2 [7]
γ_1**	134.25±0.018 [1]	0.45 [8] 0.45 [6]	α=2.3 [9] α_K=2.0±0.2* α_K=2.5 [4] α_L=0.35 [9]	5.5±0.5 [3] 5.0±0.5 [6]	M1 or M1+E2 [3] M2 or M1+E2 [4] M1 [2,6] M1+E2 [7]*
γ_6***	206.3 [3]			4.0±0.5 [3] 4.5±0.5 [6]	M1+E2 [6]
γ_3	479.52±0.19 [1]	1.00 [8] 1.00 [6]	α_K=0.022 [8]	4.2±0.5 [3] 4.0±0.5 [6]	E2 [2,3,6]*
γ_4	552 [2,6]	0.31 [8] 0.40 [6] 0.10±0.02*			E1 [2]*
γ_7	618.89±0.31 [1]	0.42 [8] 0.30 [6]		4.0±1.0 [3] 3.8±1.0 [6]	E2 [3,6]
γ_5	686.06±0.38 [1]	1.48 [8] 1.85 [6]		5.0±1.0 [3]	E2 [3], E1 [2]*

*Results of the present work.

**L$_3$/L$_1$ = 1/60,[3] L/M = 3.5 ± 0.5.[6] The ratio of the radiation amplitudes of the mixture E2 and M1 in the 134-kev γ transition amounts to $(2.2 \pm 0.5) \times 10^{-2}$.

***The ratio of the intensity of the 206-kev γ-quanta to the intensity of the unconverted 134-kev γ-quanta is less than $\frac{1}{30}$.[2] The lifetime of the 206-kev level energy is $T_{1/2}$ = 0.51 ± 0.02 μsec.[10]
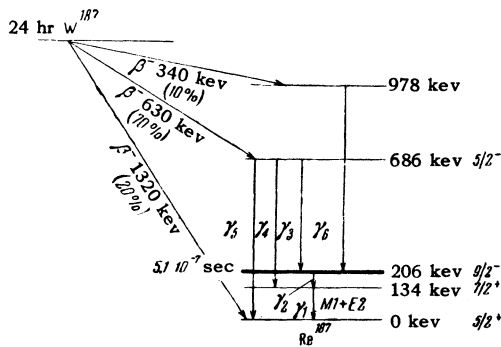
FIG. 1. Decay scheme of W^{187}.

and amplitude selection with the help of an ampli-
tude analyzer, the pulses from the light flashes in
the crystals entered a multi-channel delayed-co-
incidence circuit. The circuit made possible meas-
urements with a delay time of from 0 to 1 μsec.
The number of channels of the coincidence circuit
used varied from 3 to 6, depending on the nature
of the problem. The resolving power τ of each
channel also varied from 1.5×10^{-8} to 10^{-7} sec.
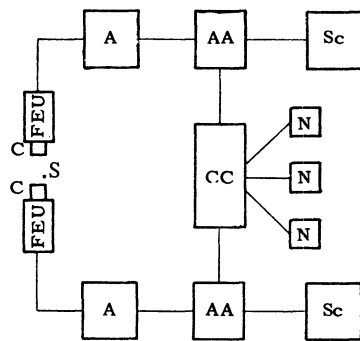A single count was registered by scalers.

FIG. 2. Block diagram of the measuring set-up: S — source;
C — crystals of NaI(Tl); FEU — photomultipliers; A — amplifiers;
AA — amplitude analyzers; CC — multichannel delayed coinci-
dence circuit; Sc — scaler; N — electromechanical counters.

The apparatus allowed the taking of instanta-
neous and delayed coincidence spectra, the de-
termination of internal conversion coefficients
and the measurement of angular correlations. The
lifetime of the metastable state of Re^{187} was meas-
ured earlier in similar apparatus.[10]

Gamma-ray spectra of Re^{187}, obtained with the
help of the apparatus described, are shown in Figs.
3 and 4.

MEASUREMENTS AND RESULTS

The single (Fig. 3) and coincidence (Fig. 4)
γ-ray spectra of Re^{187} obtained in the present
work are completely analogous to the spectra of
reference 4. However, the 552-kev γ line, which
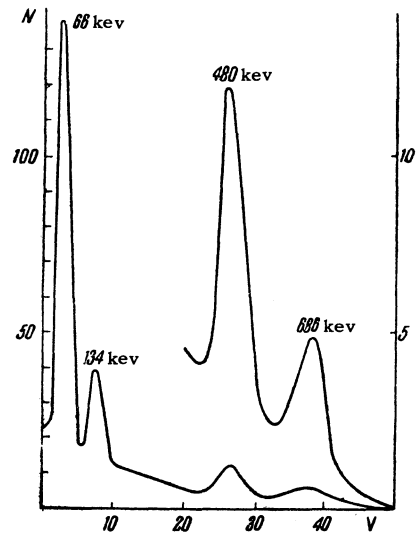is not seen in the single spectrum (Fig. 3) and

FIG. 3. Single spectra of Re^{187} γ rays (for the upper curve
the reading of N is on the right-hand ordinate axis; V is the
bias voltage).

did not appear in the coincidence spectra of ref-
erence 4, was clearly obtained in the spectrum
of instantaneous coincidences with the 134-kev
γ line, shown in Fig. 4. From the ratio of the
areas of the photopeaks at 480 and 552 kev (Fig. 4),
taking into account the experimentally determined[11]
efficiency of the NaI crystal, the resolving power
of the coincidence circuit of 2τ and the lifetime
of the 206 kev energy excited level, a value of
0.10 ± 0.02 was obtained for the ratio of the in-
tensities $I(552)/I(480)$ of the γ-lines, which
is four times less than the value obtained for this
ratio in reference 6. As is evident from Fig. 4,
the slits of the amplitude analyzer could, by suit-
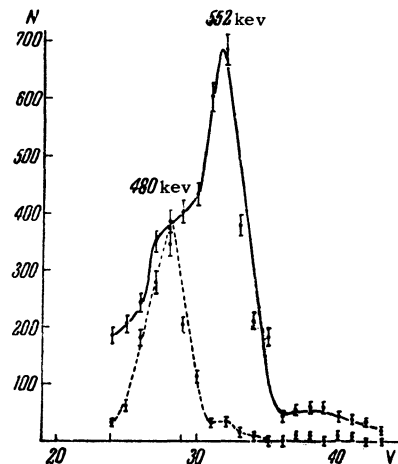able adjustment, almost completely separate the

FIG. 4. Section of the γ-coincidence spectrum with 134-kev
line in Re^{187}. The solid line is the instantaneous-coincidence
spectrum, the dotted, the delayed-coincidence spectrum taken
for a delay time $t_d = 0.1$ μsec. The resolving powers of the
channels of the coincidence circuit is $\tau = 1.6 \times 10^{-8}$ sec.

552 kev γ line from the 480 kev γ line. This circumstance was used for the determination of the internal-conversion coefficient α_K^{134} in the K shell for the 134-kev γ transition, and also for the measurement of the angular correlation of the 552 — 134 kev γ cascade. The coefficient α_K^{134} was determined from the ratios of the areas of the photopeaks of the x-ray K line of Re and the 134-kev γ line in the coincidence spectrum with the 552-kev γ line. After introducing corrections for the efficiency of the NaI crystal, for the fluorescence yield of Re, and for absorption of the γ and x-radiation in the equipment (the total of all the corrections was 5%), a value $\alpha_K^{134} = 2.0 \pm 0.2$ was obtained.

In the measurements of the angular correlation of the 552 — 134 kev cascade, as in all other measurements, a preparation of W^{187} was used, obtained by the reaction $W^{186}(n, \gamma)W^{187}$. In the majority of cases the target was a tungsten wire of diameter 0.2 mm, from which sources with lengths from one to several millimeters were directly prepared. The distance from the source to the NaI crystal was 70 mm. The 552-kev γ line was registered by the first counter, in which a 20 mm high NaI(Tl) crystal served as a detector, while the slit of the amplitude analyzer was set so that the contribution of the 480-kev γ line did not exceed 5%. The second counter with a 13 mm high NaI crystal registered the 134-kev γ line. As a precaution against Compton scattering from one crystal into the other, which would lead to false coincidences, the NaI crystal of the first counter was covered by a lead filter 3 mm thick in front and 4 mm thick on the side surfaces. Coincidences were registered in a three-channel circuit. Two of these channels served as monitors: in the case of a normally working circuit and accurate set-up of the slit of the amplitude analyzers, these channels could not register any coincidences except random ones. The resolving time of the coincidence channels was determined by random coincidences from independent sources and was equal to 2.5×10^{-8} sec in each channel. The number of coincidences at angles θ of 90, 135, and 180° alternately, with an interval of 10 minutes, was measured with the aim of determining the angular correlation function $W(\theta)$. Simultaneously with the measurement of the coincidences at a given angle, the number of single charges of the counters were determined. About 15,000 true coincidences were registered for each of the foregoing angles, θ, with the ratio of the number of true coincidences to the number of random coincidences equal to $N_t/N_r = 2$. The

average true coincidence rate was 9 counts/minute. In calculating $W(\theta)$ corrections were introduced for a variation of the single pulses in the counters, for the finite angular resolution of the detectors, and for the decay of the W^{187} source (half-life $T_{1/2} = 24$ hrs.). The contribution of the high-energy lines was not taken into account. As a result the following was obtained for the angular correlation function of the 552 — 134 kev γ cascade in Re[187]

$$W(\theta) = 1 + (0.023 \pm 0.014)\cos^2\theta,$$

Which corresponds to the sequence of transitions $\frac{5}{2}(E1)\frac{7}{2}(M1+E2)\frac{5}{2}$, if the ratio of the amplitudes of the mixture $\delta^2 = I(E2)/I(M1)$ of the 134-kev transition is taken equal to $(2.2 \pm 0.5) \times 10^{-2}$, in agreement with the Coulomb excitation data,[5] with $\delta < 0$ (see Fig. 5).
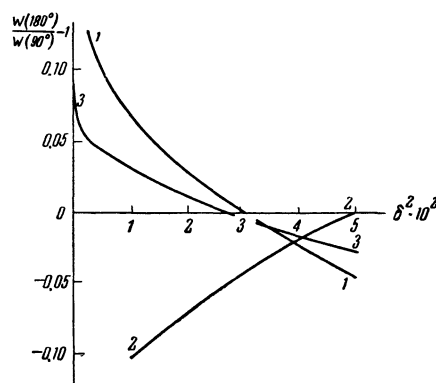

FIG. 5. Curves of $W(180°)/W(90°) - 1$ (theoretical) for the 552 — 134, 480 — 72 — 134 and 72 — 134 kev γ transitions as functions of ratio of the amplitudes $\delta^2 = I(E2)/I(M1)$ of the E2 and M1 radiation mixture of the 134-kev γ transition for the following sequences of transitions: 1) $\frac{5}{2}(E1)\frac{7}{2}(M1+E2)\frac{5}{2}$, 2) $\frac{5}{2}(E2)\frac{9}{2}(E1)\frac{7}{2}(M1+E2)\frac{5}{2}$, 3) $\frac{9}{2}(E1)\frac{7}{2}(M1+E2)\frac{5}{2}$.

Along with those described above, measurements of the angular correlations of the 480 — 134 and 72 — 134 kev γ cascades in Re[187] were made. The first measurements of the 480 — 134 kev cascade correlations were made with a five channel delayed-coincidence circuit with the width of each channel equal to $2\tau = 1.7 \times 10^{-7}$ sec. The sixth channel of the circuit registered the zero-delay coincidences. Thus the behavior of the function $W(\theta)$ of the indicated cascade could be studied in its dependence on the delay time over the interval from 2×10^{-7} to 10^{-6} sec. The measurement conditions were similar to those described earlier, the only difference being that no measures were taken to protect against scattering from crystal to crystal, since this effect does not give delay coincidences. Besides, the measurements were made not only with metallic, but with liquid sources, aqueous solutions of ammonium tungstate.

The angular distribution of the $480 - 134$ kev γ cascade for all five channels of delayed coincidences turned out to be isotropic within 1 to 2%, both in the case of solid and in the case of liquid sources. Inasmuch as this fact can be explained by disruption of the angular correlation, owing to the interaction between the Re^{187} nucleus in the intermediate state and the fields external to the nucleus,[12] the measurements were repeated using only one channel with instantaneous coincidences. Here the resolving power τ of this channel was decreased to 1.5×10^{-8} sec, and for protection from scattering of radiation from crystal to crystal a lead filter was again used. The true coincidence counting rate in this series of measurements consisted on the average of 4 counts/minute with an N_t / N_r ratio ≈ 1.3. For each of the three angles θ (90, 135, and 180°), about 8000 true coincidences were obtained. After correcting for the finite angular resolution of the detectors, that the coefficient a_2 was found to equal -0.04 ± 0.02, if the correlation function has the form $W(\theta) = 1 + a_2 \cos^2 \theta$. If we take into account in the measurements the contribution of the 552-kev γ line (this contribution amounts to $(35 \pm 5)\%$ of the contribution from the 480 kev γ-line), then a_2 is found to be -0.06 ± 0.04. This result agrees best of all with the data of the measurement of the $552 - 134$ kev cascade in the case of the transition sequence $\frac{5}{2}(E2) \frac{9}{2}(E1) \frac{7}{2}(M1+E2) \frac{5}{2}$. Here the ratio of the amplitudes of the mixture in the last transition (134 kev) $\delta^2 = (2.5 \pm 1.5) \times 10^{-2}$; $\delta < 0$ (Fig. 5).

If the foregoing arrangement of moments and multipolarities are correct, the angular correlations of the $72 - 134$ kev γ cascade must correspond to the transition sequence $\frac{9}{2}(E1) \frac{7}{2}(M1 + E2) \frac{5}{2}$. The measurement results turned out to be in agreement with this conclusion. It is impossible to use a frontal lead filter for protection against scattering from crystal to crystal in the measurement of the angular correlation of the $72 - 134$ kev cascade. Therefore only one lead side screen was used, but the measurements were made for θ equal to 30, 45, 60 and 90° in such a geometry that the side screen completely excluded the possibility of registering quanta scattered from crystal to crystal. The resolving time of the coincidence circuit was 1.5×10^{-7} sec, and the distance from the source to the NaI crystal was 100 mm. Under these conditions a value 0.009 ± 0.010 was obtained for the coefficient a_2. In the separation of the 72-kev photopeak, we registered the K-shell x-rays from Re, formed as a result of in-ternal conversion. The radiation due to these coincidences possesses an isotropic angular distribution. Knowing the conversion coefficients for the corresponding transitions, we can calculate the contribution of the x-rays to the measured correlation. In the case of the sequence of transitions $\frac{9}{2}(E1) \frac{7}{2}(M1+E2) \frac{5}{2}$ the 72-kev γ transition is E1. Utilizing the theoretical values for the K- and L-shell internal conversion coefficients, the $\alpha_K = 0.5$ (reference 13) and $\alpha_L = 0.14$,[14] and also taking into account the contributions of the 480 and 552 kev γ lines in a manner similar to that used in reference 7, we find $a_2 = 0.015 \pm 0.017$.

We obtain therefore for the ratio of the 134-kev transition amplitudes $\delta^2 = (1.7 \pm 0.7) \times 10^{-2}$; $\delta < 0$ (see Fig. 5).

CONCLUSION

The results of the present work confirm the assignment of the angular momenta of the excited states and the multipole types of the Re^{187} γ transitions proposed in the decay scheme of reference 15. According to this scheme, the 206-kev metastable state of Re^{187} has a spin $\frac{3}{2}$ and negative parity. In reference 7 a spin of $\frac{9}{2}$ and positive parity were ascribed to the indicated state on the basis of measurements of the angular correlation of the $72 - 134$ kev γ cascade. However, it seems unlikely that a 206-kev state possessing the same parity as the ground state and differing from the latter in momentum only by unity would have so long a lifetime.

[1] Müller, Hoyt, Klein, and Du Mond, Phys. Rev. **88**, 775 (1952).

[2] A. W. Sunjar, Phys. Rev. **90**, 387 (1953).

[3] Cork, Brice, Nester, Le Blanc, and Martin, Phys. Rev. **89**, 1291 (1953).

[4] E. Germagnoli and A. Malvicini, Nuovo cimento **10**, 1388 (1953).

[5] Davis, Divatia, Lind, and Moffeat, Phys. Rev. **103**, 1801 (1956).

[6] Dubey, Mandeville, Ambuj Mukerje and Potnis, Phys. Rev. **106**, 785 (1957).

[7] L. J. von Behrend and H. Neuert, Z. Naturforsch. **A13**, 208 (1958).

[8] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

[9] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956).

[10] P. I. Shavrin and V. S. Avzyanov, Тезисы докладов VII ежегодного совещания по ядерной спектроскопии (Theses of Reports of the VII Annual Conference on Nuclear Spectroscopy), U.S.S.R. Acad. Sci. Press, 1957.

[11] Kalinkin, Melioranskiĭ, and Estulin, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 592 (1958), Soviet Phys. JETP **8**, 410 (1959).

[12] A. Abragam and R. V. Pound, Phys. Rev. **92**, 943 (1953).

[13] B. J. Spinrad, Phys. Rev. **98**, 1032 (1955).

[14] L. A. Sliv and I. M. Band, Таблицы коэффициентов внутренней конверсии гамма-излучения. Ч. 2. L-оболочка, (Tables of Gamma-radiation Internal Conversion Coefficients. Part 2. L-shell) U.S.S.R. Acad. Sci. Press, 1958.

[15] B. S. Dzhelepov, and L. K. Peker, Схемы распада радиоактивных изотопов, (Decay Schemes of Radioactive Isotopes) U.S.S.R. Acad. Sci. Press, 1957.

Translated by M. A. MacLeod
269