# Angular Correlation in $Os^{188}$†

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(Received January 12, 1956)

The quantum radiations of $Re^{188}$ have been examined with the aid of coincident scintillation spectrometers. In addition to those already known, gamma rays have been detected at energies of 1300 and 1770 kev. The spatial correlation function of the 480 kev–150 kev cascade has been determined and corresponds to a 2-2-0 scheme with $E2$ heavily mixed (99.56%) in $M1$ in the case of the 480-kev transition.

## INTRODUCTION

THE radiations of the 18-hour $Re^{188}$ have been previously studied with coincident Geiger counters[1] and beta-ray spectrometers,[2] and McMullen and Johns[2] have proposed a decay scheme which includes seven gamma rays. In the present investigation, the gamma-ray spectrum has been viewed with scintillation counters, and a correlation study has been carried out to determine the spin values of the first and second excited states of $Os^{188}$.

## THE MEASUREMENTS

The 18-hour rhenium was formed by irradiation of four separate samples of metallic Re by slow neutrons for a period of two hours each in the Brookhaven pile. Owing to the short exposure time, little of the 96-hour $Re^{186}$ was produced. Measurements were usually commenced within ten hours after cessation of exposure and were continued for approximately thirty-six hours thereafter.

The energy distribution of the gamma rays of $Re^{188}$ as measured in a scintillation spectrometer of NaI(Tl) is shown in Fig. 1. Absorbers were employed to reduce the intensity of the 150-kev gamma ray which is far more intense than the other quantum radiations present. Suppression of its intensity made possible utilization of a strong source for detection and study of weak radiations of higher energies.

Photopeaks are present at energies of 150, 480, 630, 820, 910, 1130, 1300, 1600, and 1770 kev. The same spectrum as observed sixteen hours later is also shown. From the extent of decay of the ordinates of the curve at all energies, it is clear that all gamma rays present have the same lifetime (about eighteen hours). It was noted that the relative heights of the various photopeaks were independent of the source to crystal distance, showing that none resulted from additive simultaneous detection of two or more gamma rays of lower energy.

All the gamma rays previously reported by McMullen and Johns were detected in the present investigation. In addition, gamma rays were also observed at energies of 1300 and 1770 kev. The previously reported[2] complexity of the peak at ~630 kev was studied with application of coincidence techniques. Using channel widths of one volt, one channel of the coincidence spectrometer was fixed at 150 kev whereas the other channel was moved through the region of energy extending from 470 to 700 kev. The 480-kev gamma ray was found to be coincident with the 150-kev gamma ray as shown in Fig. 2(A). In Fig. 2(B), the peak of the coincidence rate appears to be shifted to an energy greater than 630 kev, indicating the presence of more than one gamma ray. From the gamma-gamma coincidence rate, it was possible to estimate that the 660-kev transition had an intensity of less than 2% of the 630-kev transition. The conversion coefficients of the 630- and 680-kev gamma rays have been neglected in making this comparison of intensities. The relative intensities of the unconverted quantum radiations have been estimated, taking into account absorption of the radiations in all materials intervening between the source and the crystalline NaI(Tl), the variation with energy of the detection efficiency of the crystal, and the similar variation of the photopeak to Compton cross-

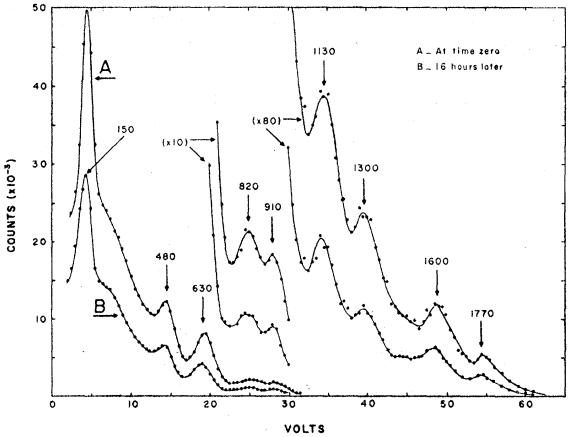


FIG. 1. Energy spectrum of the gamma rays from $Re^{188}$.

† Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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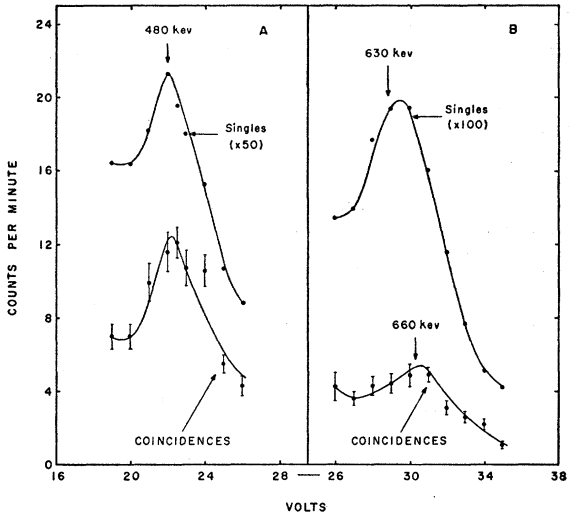


FIG. 2. Gamma-gamma coincidences in the decay of $Re^{188}$ with one counter fixed at the photopeak of the 150-kev radiation. Curve *A*, with the moving counter in the region of 480 kev; Curve *B* in the vicinity of 660 kev.

section ratio. The relative intensities of the gamma rays are given in Table I.

The angular correlation of the 480 kev–150 kev cascade has been measured using pulse-height selection in either channel. The lifetime of the 150-kev transition has been reported[3] to be $6.5\times10^{-10}$ sec; so an unperturbed correlation would be expected. Since the nucleus of $Os^{188}$ is even-even in character, and since the cross-over transition of the 480 kev–150 kev cascade is present, the spins of the first and second excited states might be expected to be each 2+. The resolving time of the coincidence circuit employed in the correlation study was 0.2 $\mu$sec. The fixed counter was set at the photopeak of the 150-kev gamma ray, and counts falling in a channel width of a single volt were accepted. The other counter was so arranged as to count in a 4-volt channel width pulses falling in the photopeak of the 480-kev gamma ray.

The source was metallic rhenium contained in a small carbon cylinder which was sufficiently thick to stop all beta rays of $Re^{188}$. The use of carbon as an absorber for beta rays minimized production of external bremsstrahlung. The distance of the source from the face of each crystal was 6 cm, and the half-angle of the detecting system was 12.5 degrees as measured with the use of the annihilation radiation of $Na^{22}$. Measurements were carried out at five angles, the moving counter being placed at intervals of 22.5 degrees between the angles of 90 and 180 degrees with the axis of the fixed counter. Coincidences and single counts were accumulated at each angle over a period of five minutes at a time. By moving through the range of angles repeatedly, decay corrections were eliminated. Gamma rays of energy greater than 480 kev are also coincident with the 150-kev radiation. Compton recoils of these gamma rays may also contribute to the coincidence rate, but this effect has been minimized by utilization of pulse height selection. Between seven and nine thousand coincidences have been collected at each angle.

TABLE I. Energies and relative intensities of the gamma rays of $Re^{188}$.

| Gamma-ray energy (kev) | Relative intensity |
|---|---|
| 150 | 101.0 |
| 480 | 12.0 |
| 630 | 16.0 |
| 660 | 0.3 |
| 820 | 6.5 |
| 910 | 5.8 |
| 1130 | 2.7 |
| 1300 | 2.2 |
| 1600 | 2.1 |
| 1770 | 1.0 |

[3] A. W. Sunyar, Phys. Rev. **95**, 626(A) (1954).

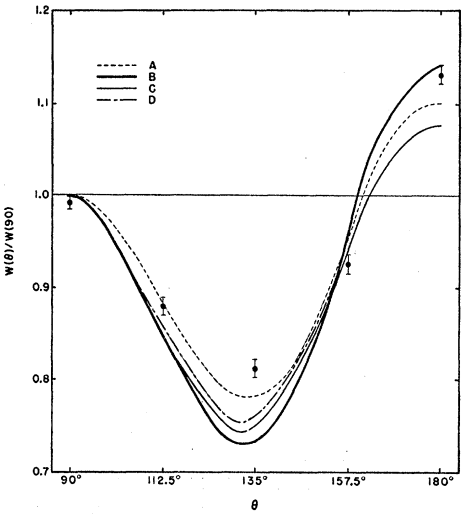


FIG. 3. Angular correlation function of the 480 kev–150 kev cascade in the de-excitation of $Os^{188}$. On the interval extending from 157.5° to 180°, the curve of the $E2-M1$ mixture (99.56% $E2$) is coincident with the observed curve corrected for resolution of the detectors. Curve *A*, least-squares fit of observed points; Curve *B* is Curve *A* corrected for angular resolution of the detectors and replotted; Curve *C*, theoretical correlation function for decay scheme $2(E2)2(E2)0$. Curve *D* is expected for $2(99.56\%\ E2, 0.44\%\ M1)2(E2)0$.

The results of the angular correlation measurements are shown in Fig. 3. The observed points are shown along with their indicated statistical errors. A "least squares" fit of the data yielded the function

$$W(\theta)=1-0.97\cos^2\theta+1.08\cos^4\theta.$$

The probable errors of the terms in $\cos\theta$ are less than five percent. When this equation is modified for angular resolution, the correlation function becomes

$$W(\theta)=1-1.20\cos^2\theta+1.34\cos^4\theta.$$

The curves of the two preceding equations are plotted

in Fig. 3 along with the theoretically expected correlation function of a 2−2−0 spin sequence and pure quadrupole-quadrupole transitions. The observed anisotropy at 180°, 0.14, is greater than would be expected for such a cascade of transitions. Accordingly, a theoretical correlation function with the first emitted gamma ray a mixture of $E2$ in $M1$ to the extent of 99.56%, has been plotted and appears to agree well with the observed correlation function corrected for finite angular resolution. Thus it is concluded that the 480-kev gamma ray is a mixture of $E2$ in $M1$ with the aforementioned percent of mixture. The mixing ratio was found to be positive, corresponding to a phase difference of 180° between the matrix elements of the two types of transition.

### ACKNOWLEDGMENTS

The writers wish to acknowledge the kind interest of Dr. W. F. G. Swann, Director of The Bartol Research Foundation. Research appointments at the Foundation have made possible the stay of the Indian authors in the United States.

PHYSICAL REVIEW VOLUME 102, NUMBER 2 APRIL 15, 1956

# Gamma Radiation from Inelastic Scattering of Fast Neutrons by Isotopes of Tellurium, Nickel, and Copper*

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(Received January 9, 1956)

Gamma radiation from 4.4±0.1 Mev neutron bombardment of separated isotopes was observed with a single crystal NaI(Tl) spectrometer. Gamma rays assigned to inelastic scattering are (energies in Mev): $Te^{126}$, 0.68±0.02, 1.38±0.04; $Te^{128}$, 0.76±0.02; $Te^{130}$, 0.83±0.02; $Ni^{58}$, 1.01±0.01, 1.46±0.02; $Cu^{63}$, 0.65±0.01, 0.97±0.01, 1.34±0.03, 1.43±0.05; $Cu^{65}$, 1.12±0.02. A 1.35±0.02 Mev gamma ray is assigned to $Ni^{60}$ by elimination. Relative yields of the gamma rays are given and their assignment to various excited states of the target nuclei is discussed.

## INTRODUCTION

THE study of fast neutron scattering by observations of the de-excitation gamma rays has received considerable attention in the past few years. The technique has proved useful for monoisotopic elements with widely spaced excited states, so that the various gamma rays can be resolved with the commonly used scintillation counters. The use of enriched isotopes as scatterers now makes possible the study of polyisotopic elements for which the gamma rays from the various isotopes in an elemental scatterer cannot be resolved because of instrumental overlap. The isotopic assignments that can be made allow more positive correlations of these gamma rays with quantities measured by other experimental methods.

Gamma ray energies and yields can be used, together with general arguments based on nuclear systematics, to locate the excited states. These assignments cannot be unambiguous unless other data on the approximate location of the levels, preferably from measurements of the scattered neutron spectra, are available. The gamma ray energies can then be used to locate these levels accurately.

## EXPERIMENTAL

The experimental method has been described previously.[1] Neutrons of energy 4.4±0.1 Mev were

TABLE I. Isotopic composition (percent) and weight (grams) of tellurium samples.[a]

| Isotope | $Te^{125}$ Sample No. 1[b] | $Te^{125}$ Sample No. 2[c] | $Te^{126}$ Sample No. 1[d] | $Te^{126}$ Sample No. 2[e] | $Te^{128}$ Sample No. 1[f] | $Te^{128}$ Sample No. 2[g] | $Te^{130}$ Sample No. 1[h] | $Te^{130}$ Sample No. 2[i] | Normal Te |
|---|---|---|---|---|---|---|---|---|---|
| $Te^{120}$ | ··· | <0.030 | <0.001 | 0.045 | 0.042 | <0.1 | 0.013 | 0.039 | 0.090 |
| $Te^{122}$ | 0.1 | 0.112 | 0.096 | 0.055 | 0.097 | <0.1 | 0.020 | 0.032 | 2.47 |
| $Te^{123}$ | 0.3 | 0.140 | 0.034 | 0.043 | 0.027 | <0.1 | 0.020 | 0.020 | 0.89 |
| $Te^{124}$ | 1.4 | 1.98 | 5.60 | 0.247 | 0.480 | <0.1 | 0.052 | 0.030 | 4.74 |
| $Te^{125}$ | 87.9 | 80.53 | 0.661 | 1.33 | 0.502 | 0.2 | 0.077 | 0.051 | 7.03 |
| $Te^{126}$ | 6.8 | 12.66 | 89.68 | 93.46 | 12.84 | 1.5 | 0.513 | 0.164 | 18.72 |
| $Te^{128}$ | 2.4 | 3.36 | 3.32 | 3.95 | 82.32 | 94.4 | 21.07 | 1.88 | 31.75 |
| $Te^{130}$ | 1.1 | 1.19 | 0.609 | 0.852 | 3.69 | 3.9 | 78.23 | 97.78 | 34.27 |
| Weight | 1.58 | 1.27 | 4.35 | 3.19 | 8.72 | 5.67 | 4.65 | 3.35 | 45.7 |

[a] Other elements are present in negligible amounts. [b] Oak Ridge National Laboratory Lot No. CA296(ar). [c] FE644(a). [d] DX510(a). [e] FE645(a) [f] DX511(a). [g] CA298(a). [h] DX512(a). [i] FE647(a).

* Assisted in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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