Nuclear Energy Levels of Os^{188}†

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(Received June 21, 1956)

The beta and gamma radiations of the 18-hour Re^{188} have been examined with scintillation and magnetic spectrometers. Of the total beta disintegrations, 79% lead to the ground state, 20% to the first excited state at 155 kev, and 1% to the other excited states of Os^{188}. The beta-ray spectra leading to the ground state and the first two excited states of Os^{188} are first forbidden. Thirteen gamma rays have been detected. Extensive gamma-gamma coincidence studies were made. The K-shell conversion coefficient of the 155-kev gamma ray has been obtained which agrees quite well with the $E2$ assignment for that gamma ray. The K/L ratio also supports this assignment. No conversion electrons corresponding to the 478-kev gamma ray were found and it is concluded that it is primarily $E2$ in nature with a small admixture of $M1$ transition. A decay scheme is proposed on the basis of these data.

INTRODUCTION

NATURAL rhenium metal has two stable isotopes, Re^{185} and Re^{187}. Slow-neutron bombardment produces two activities, Re^{186} and Re^{188}, with half-lives of 92 and 18 hours, respectively. Re^{186} decays by electron capture to W^{186} and by electron emission to Os^{186}. Re^{188} decays by electron emission to Os^{188}. In all these modes of decay, the product nucleus is even-even in character. Because of an appreciable difference in the half-lives, it is not difficult to assign the radiations to the proper isotope. Moreover, the yield of the activities can be controlled by varying the bombarding time. In earlier studies, and, indeed, in more recent investigations,[1,2] natural rhenium metal has been used to produce the activities. In the present study, rhenium enriched in Re^{187} has been used to produce Re^{188}. NaI(Tl) scintillation spectrometers and a thin-lens magnetic spectrometer have been used in making the measurements.

RHENIUM-188

Isotopically enriched (98.22%) Re^{187} was bombarded by slow neutrons in the Brookhaven pile for a period of 24 hours. Several samples of 25 mg each were employed. In each case, the measurements were commenced within 12 hours after the target material was removed from the pile, and were continued for about three days thereafter.

The gamma-ray spectrum of Re^{188}, as revealed in a scintillation spectrometer, is shown in Fig. 1. Enough carbon was placed on the top of the crystal to absorb the beta rays and reduce the external bremsstrahlung. Four photopeaks are clearly visible at energies 62, 155, 478, and 633 kev. The smaller peak near 30 kev arises from the escape pulses of the 62-kev K x-rays of osmium, which are emitted after internal conversion of some of the gamma rays. Several high-energy gamma rays of low intensity are also present. In order to study these radiations of higher energy, a strong source was used and the intensities of the 155-kev gamma ray and 62-kev x-rays were reduced by introduction of suitable absorbers. The pulse height distribution of the gamma rays obtained under these conditions is shown in Fig. 2. All of the gamma rays reported in recent studies[1,2] are seen to be present. The half-life of all the gamma rays was found to be about 18 hours. Thus these gamma rays are definitely emitted in the decay of Re^{188}. From Figs. 1 and 2 an estimate of the unconverted quantum intensities can be made, after applying the proper corrections for absorbing material between the source and the crystal, detection efficiency for the gamma rays of various energies, and photopeak to Compton ratio variation with gamma-ray energy. The intensities so obtained are given in Table I.

These intensity values agree fairly well with the previous estimates.[1,2] However, Johns'[2] estimate of the intensity of the 155-kev gamma ray relative to that of the 633-kev gamma ray is about 1.5 times the present one.

GAMMA-GAMMA COINCIDENCES

The gamma ray of 155-kev energy has been found[2] to be in coincidence with all other gamma rays except the 633- and 1960-kev gamma rays. The complexity of

TABLE I. Unconverted quantum intensities.

Gamma-ray energy in kev	Relative intensity
155	6.30
478	0.67
633	0.98[a]
660	0.02[a]
	1.00
828	0.35
931	0.43
1132	0.08
1307	0.14
1610	0.13
1780	0.06
1805	0.03
1960	0.03

[a] These intensities are from reference 1.

† Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] Potnis, Dubey, and Mandeville, Phys. Rev. 102, 459 (1956).
[2] M. W. Johns *et al.*, Can. J. Phys. 34, 69 (1956). (Other references may be found in these papers.)

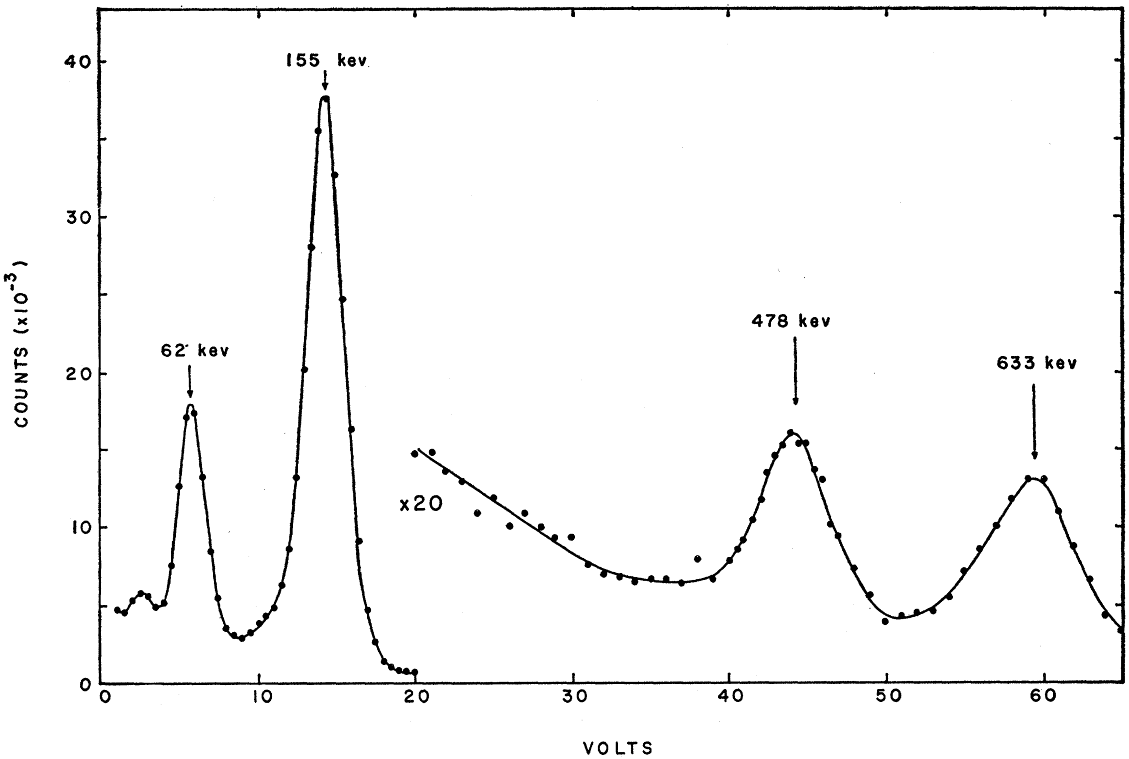

FIG. 1. Energy spectrum of gamma rays from Re^{188}.

the 633-kev photopeak was shown[1] to be due to an additional gamma ray of 660-kev energy. It has also been observed[2] that the 633-kev gamma ray is in coincidence with the 828-, 1133-, and 1308-kev gamma rays.

The data of the present coincidence experiments are shown in Fig. 3. One channel of the scintillation spectrometer was fixed on a particular gamma ray and the other was used to scan the spectrum. The region

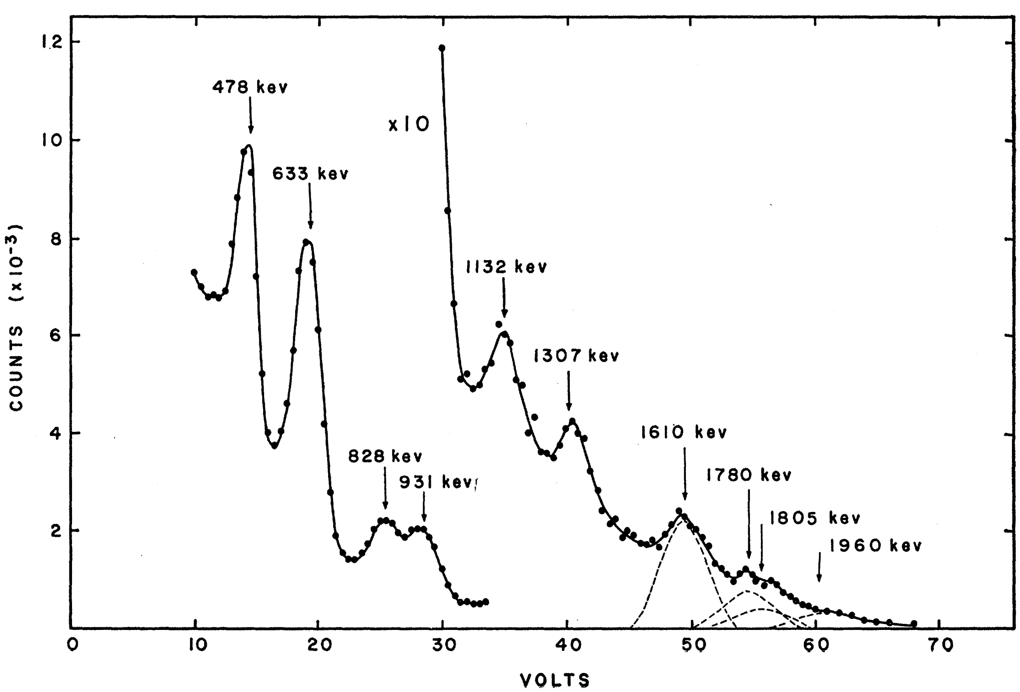

FIG. 2. Energy spectrum of gamma rays from Re^{188}. Absorbers of Pb, Cd, Cu, and Al are used. Enough carbon is placed on the top of these absorbers to reduce the external bremsstrahlung due to high-energy beta rays.

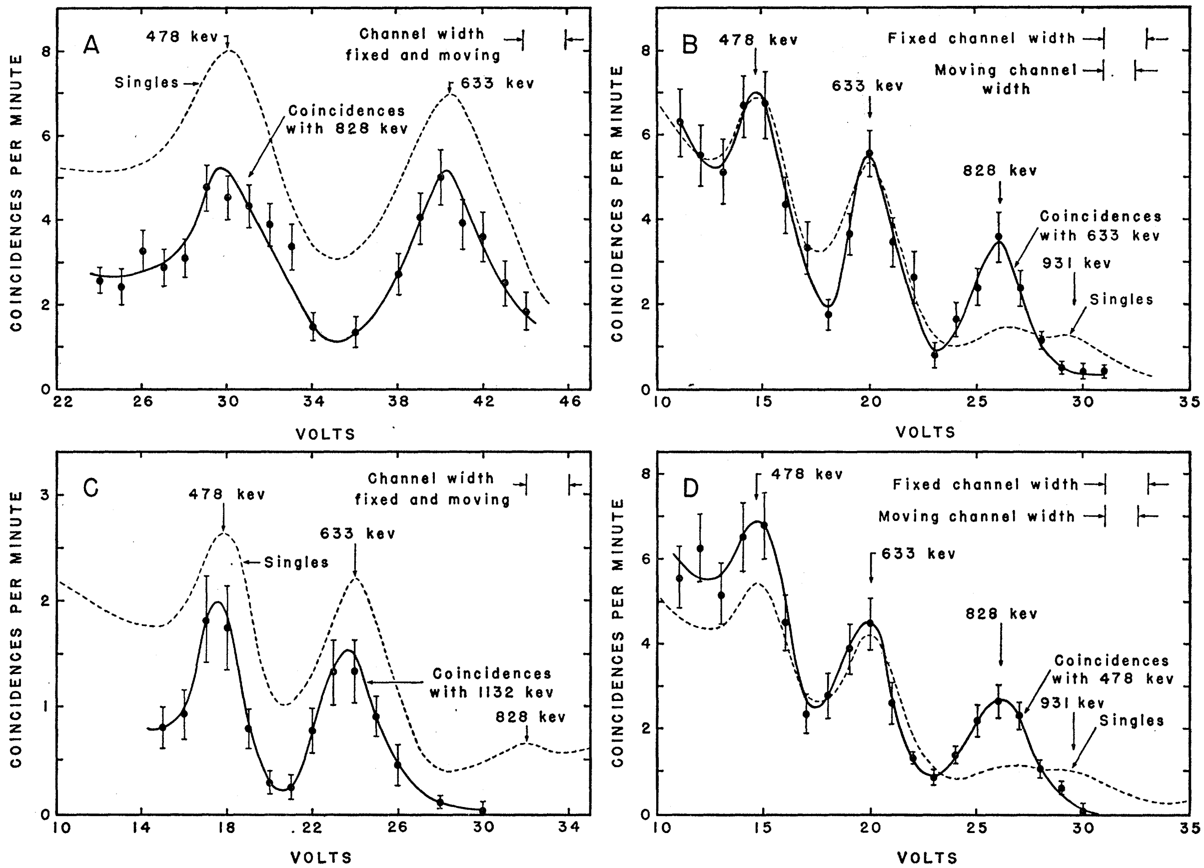

FIG. 3. Gamma-gamma coincidences observed when one channel of the scintillation spectrometer is fixed on the photopeaks at energies *A*—828 kev, *B*—633 kev, *C*—1132 kev, and *D*—478 kev.

which is scanned by the second channel is shown by the singles curve in the figure. The channel widths used are also indicated. Because of the low intensities of the gamma rays of higher energy, wide channels were used to get an appreciable number of coincidences. Although the coincidence rate was small, the ratio of true to chance coincidences was always greater than five or more.

Figure 3(A) shows the 828-kev gamma ray to be in coincidence with the 478- and 633-kev quanta. In Fig. 3(B) the fixed channel covers the composite photopeak at 633-kev energy which is seen to be in coincidence with the photopeaks at 478, 633, and 828 kev. The coincidences under the 633-kev photopeak shows that there are two gamma rays of comparable energy which are in cascade. Since the 633-kev gamma ray appears to be the crossover transition of the 155-kev—478-kev cascade, the coincidences under the photopeak at 478 kev should be due to the 478 kev—660 kev gamma-ray cascade. These data clearly show the presence of the 660-kev gamma ray and fixes its position in the decay scheme in relation to the 155- and 478-kev gamma rays. From the presence of the coincidences under the 828-kev photopeak it is difficult to say whether both 660- and 633-kev gamma rays or only one of them is in coincidence with the 828-kev gamma ray. It seems to be unlikely that all three of these gamma rays are in cascade, because the total energy corresponding to the sum of the three gamma rays would be nearly equal to the total disintegration energy available; so it is concluded that the 828-kev gamma ray is only in coincidence with the 633-kev gamma ray. No portion of the 633-kev and 660-kev photopeak is in coincidence with the 931-kev gamma ray. Figure 3(C) shows that the 1132-kev gamma ray is in coincidence with 478- and 633-kev photopeaks but not with the 828- and 931-kev photopeaks. Figure 3(D) shows that the 478-kev gamma ray is in coincidence with the 478-, 633-, and 828-kev quanta. Coincidences under the 478-kev photopeak show clearly that this peak is also complex. Two gamma rays of comparable energies are in coincidence with each other. From the same figure, it is clear that the 478-kev gamma ray is not in coincidence with the 931-kev gamma ray.

The following coincidences were performed for which no data are shown. The 931-kev gamma ray was found to be in coincidence only with the 155-kev gamma ray and with none other. In another experiment, one channel of the spectrometer was fixed so as to count all the gamma rays greater in energy than 1600 kev and the other was set to count all the gamma rays between 450 and 950 kev. No coincidences were detected, thus showing that the 478, 633, 660, 828, and 931 kev gamma rays are not in coincidence with any of the gamma rays of energies greater than 1600 kev. With these data it is possible to give the energy level diagram for Os^{188} as shown in Fig. 6.

BETA-RAY MEASUREMENTS

The beta-ray spectrum of Re^{188} were examined in a thin-lens magnetic spectrometer. A Geiger counter with a thin window made of "Nu-Skin" was used as the detector. The source was very thin and was formed by allowing evaporation of the solvent of a nitric acid solution on a very thin mica foil. The resolution thus obtained was about two percent. The internal conversion electron spectrum is shown in Fig. 4. Only the K, L, and $M+N$ electrons corresponding to the gamma ray of energy 155 kev were found to be present. From the figure, the K/L ratio for the 155-kev gamma ray is estimated to be 0.70 ± 0.05. A search for the conversion lines of the 478-kev gamma ray gave a negative result. It appears that the other higher energy gamma rays are also not converted to an appreciable extent.

The continuous beta-ray spectrum gives the Fermi plot shown in Fig. 5. The end point of the highest energy component is found to be at 2150 ± 40 kev, in good agreement with the previous values. Beta-gamma coincidences, with an anthracene counter detecting beta rays and the NaI(Tl) counter counting only the 155-kev gamma ray, gave an end point at about 2000 kev. Although no clear break is indicated at that energy on the Fermi plot, the highest energy component is extrapolated back as shown in the figure. It was

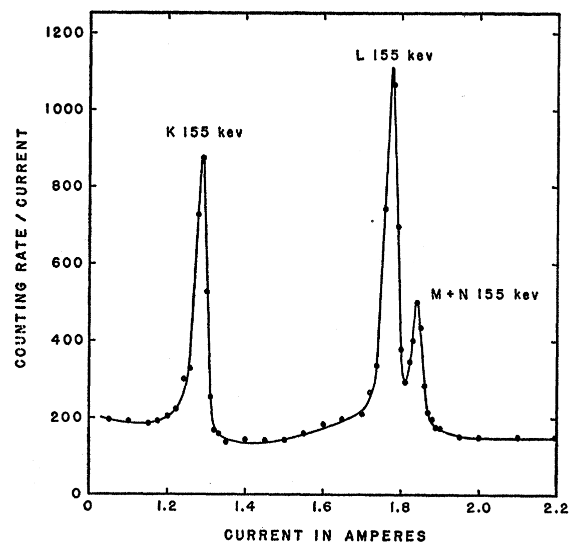

FIG. 4. Internal conversion electron spectrum of the gamma rays of Re^{188}.

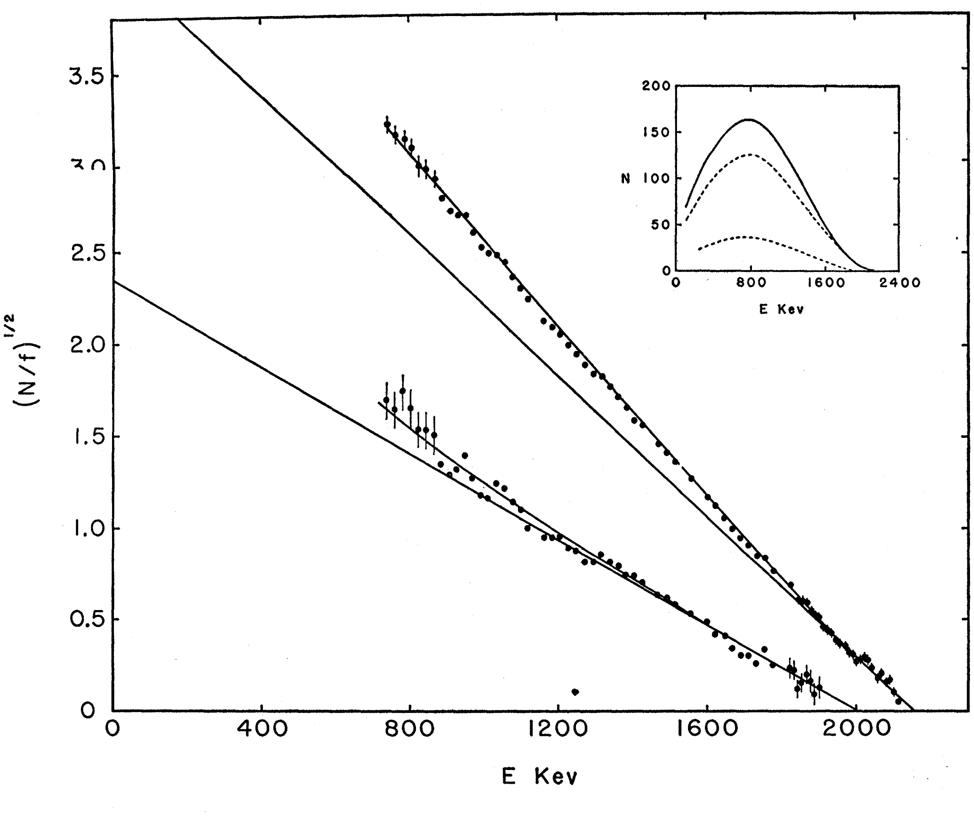

FIG. 5. Fermi plot of the beta rays of Re^{188}. N is obtained by dividing the counting rate by the current. Insert shows the resolved components drawn in broken lines. The 1% component is not shown.

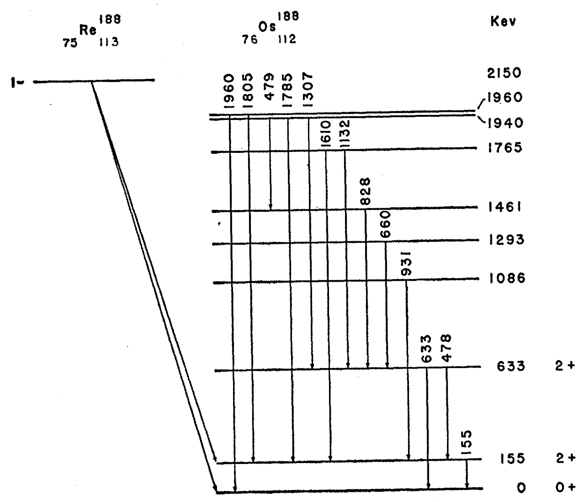

FIG. 6. Energy level diagram of Os^{188}.

assumed that both the components have an allowed shape. The percentages of the 2150- and 2000-kev components have been estimated to be 79% and 20%, respectively, which values are in excellent agreement with those of Johns.[2] About one percent of the disintegrations lead to higher levels. The values of $\log ft$ of the three components terminating at the ground, 155- and 633-kev levels in Os^{188} are estimated to be 8.1, 8.6, and 9.4, respectively. They indicate that all of the spectra are of first-forbidden degree and thus involve a parity change. When combined, the data of Figs. 4 and 5 gave the K-conversion coefficient α_K for the 155-kev gamma ray to be 0.29 ± 0.03.

The value of α_K for the 155-kev gamma ray could also be found from the data of Fig. 1. Assuming that most of the Os K x-rays arise from the internal conversion of the 155-kev gamma ray, the ratio of the areas under the x-ray photopeak to the area under the 155-kev photopeak should give the value of α_K. The data are corrected for the escape peaks of the 62- and 155-kev photopeaks, for absorption in the material intervening between the source and the crystal, for the variation of the detection efficiency of the gamma rays with energy and a similar variation in the photopeak to Compton ratio, and finally for the fluorescence yield of Os K x-rays. The value thus obtained is $\alpha_K=0.37\pm0.05$. Thus, the values of α_K calculated from two different sets of measurements are in good agreement with the value of Johns.[2] The theoretical values for α_K of the 155-kev gamma ray for $M1$, $E1$, and $E2$[3] are, respectively, 1.73, 0.11, and 0.33. These measured values clearly are in agreement with an $E2$ assignment for the 155-kev gamma ray. The K/L ratio is also in agreement with the expected value 0.70[4] for this assignment. The value 0.37 measured by the second method is somewhat higher than the theoretical one. This may arise from the presence of Os K x-rays associated with internal conversion of the higher energy gamma rays. The angular correlation measurements of the 155 kev -478 kev cascade[1] have established the spins of both the 155- and 478-kev levels to be 2. It was concluded in that measurement[1] that the 478-kev gamma ray is a mixture of 99.5% $E2$ and 0.5% $M1$ transitions. According to Johns,[2] α_K for the 478-kev gamma ray is 0.06 ± 0.02. The theoretical values[3] of α_K for $M1$ and $E2$ transitions at this energy are 0.08 and 0.02. It is suggested[2] that the 478-kev gamma ray should be a mixture of 66% $M1$ and 34% $E2$, which is in disagreement with the percentages obtained from the angular correlation data.[1] Since no conversion electrons of the 478-kev gamma rays are found in the present measurement, it is concluded that the 478-kev gamma ray is primarily $E2$ in nature with a small mixture of $M1$.

DECAY SCHEME OF $Re^{188}-Os^{188}$

The decay scheme thus obtained is shown in Fig. 6. It is in essential agreement with the one proposed by Johns,[2] with the difference that no evidence was found in the present measurements for a gamma ray of 450-kev energy as is indicated in reference 2. The complexity of the 478-kev gamma ray is explained by the presence of a 479-kev transition as shown in the decay scheme which fact explains the coincidence data of Fig. 3(D). The ground state of Os^{188} has spin zero with even parity as is expected for an even-even nucleus. The first-forbidden nature of the beta-ray spectra indicates that the ground state spin of Re^{188} should be 1 or 2 with odd parity. The level order for protons in the 50–82 shell is indicated[5] to be $g_{7/2}{}^8$, $d_{5/2}{}^6$, $h_{11/2}{}^{12}$, $d_{3/2}{}^4$, $s_{1/2}{}^2$. Hence, the 75th odd proton could either be $d_{5/2}$ or $d_{3/2}$. Similarly, the level order for neutrons in the 82–126 shell is[5] $f_{7/2}{}^8$, $h_{9/2}{}^{10}$, $p_{3/2}{}^4$, $f_{5/2}{}^6$, $p_{1/2}{}^2$, $i_{13/2}{}^{14}$. So the 113th odd neutron should have orbital $p_{1/2}$. If the orbital of the proton is assumed to be $d_{5/2}$ and that of the neutron $p_{1/2}$, then according to the Nordheim[6] strong-coupling rule the spin of the ground state of Re^{188} could only be 2. If it is supposed that the orbital of the proton is $d_{3/2}$ and that of the neutron is $p_{1/2}$, Nordheim's weak-coupling rule admits the possibilities of a ground-state spin of 2 or 1 for Re^{188}. If the ground-state of Re^{188} had a spin value of 2 with odd parity, the shape of the ground state beta transition would be "α" in character ($\Delta I=2$; yes). Since the said spectrum is highly dominant in percentage of transitions, the Fermi-Kurie plot of the experimentally observed points should have shown the usual high-energy "bulge" upward, if the spectrum were of the "α" type. Hence, the spin 1 for

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[4] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
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[6] L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).

the ground state of the Re^{188} appears to be more probable.

The 155-kev level is indicated[7] as a rotational level. If it be so, the subsequent levels should be at 516.6, 1085, 1860 kev with spins 4, 6, and 8 and with even parity. The 1086-kev level found experimentally tallies rather closely with the one expected as a rotational level. However, if the spin assignments suggested are indeed the case, the presence of the 931-kev gamma ray with its observed intensity is difficult to explain.

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ACKNOWLEDGMENT

The writer wishes to express his appreciation to Dr. C. E. Mandeville for his guidance, to Mrs. Mary Elizabeth Brandt, Mrs. Marian Patterson, and Mrs. Erma Rodgers for their kind assistance in preparation of the manuscript. The help of Mr. W. B. Todd in making the beta-ray spectrometer measurements is appreciated. Finally, the writer is grateful to Dr. W. F. G. Swann for his kind interest.

PHYSICAL REVIEW VOLUME 104, NUMBER 3 NOVEMBER 1, 1956

Energy Levels of Si^{28}†

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(Received July 30, 1956)

The neutron spectrum from the $Al^{27}(d,n)Si^{28}$ reaction has been investigated at eight angles by means of nuclear emulsions. The energy of the incident deuterons was 2.167±0.015 Mev. The data indicate energy levels of Si^{28} at 1.78±0.10, 4.54±0.2, 4.95±0.2, 6.24±0.06, 6.88±0.06, 7.39±0.06, 7.89±0.06, 8.31±0.10, 8.57±0.08, 9.37±0.04, 10.00±0.10, and 10.25±0.06 Mev.

INTRODUCTION

It is of interest to study alpha-particle nuclei because of the partial success of the alpha-particle model in correlating theory with experiment in light alpha-particle nuclei, for instance[1] in O^{16}. We have used the nuclear emulsion technique to study the reaction $Al^{27}(d,n)Si^{28}$ in order to obtain more accurate values for the energies of the excited states of $_{14}Si^{28}$. In a future paper it is hoped to present evidence on the parities of many of these states.

The position of the first excited state has been extensively investigated,[2–8] and its spin and parity have been found. The region of excitation above 11.8 Mev in Si^{28} shows many levels, found by studying resonances in the yield of reactions involving Si^{28} as the compound nucleus. These are listed in the compilation of Endt and Kluyver.[9] The intermediate region, between 1.8 and 11.8 Mev, has been investigated by Rutherglen,[8] Casson,[10] Hattori,[11] Peck,[12] and Calvert.[13] In these experiments possible ambiguousness in the interpretation of the results or lack of accuracy in energy measurements precluded the precise determination of level energies. Bent *et al.*[14] used a magnetic lens pair spectrometer to find the energies of the γ rays from the reaction $Al^{27}(d,n)Si^{28}$. The interpretation of the origin of these γ rays is sometimes obscure, since they may come either from direct transitions to the ground state or by cascades through excited states. The accuracy of their energy measurements, however, is comparable to or better than those of the present experiment, as can be seen in Table I.

EXPERIMENTAL PROCEDURE

A thin aluminum target having a thickness corresponding to an energy loss, for deuterons, of 15 kev

† This research was supported by the United States Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.

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