Search for Double Beta Decay in Ca^{48}†

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(Received June 11, 1954; revised manuscript received November 29, 1954)

If double beta decay occurs without the emission of neutrinos, the total kinetic energy of the two emitted electrons is constant. An experiment has been performed using this constancy of energy and the coincidence nature of the activity in an attempt to observe and identify this process in Ca^{48}.

The results show a peak in the total energy spectrum at 4.1±0.3 Mev. Mass spectrographic data gives 4.3±0.1 Mev as the available energy for double beta decay. The author believes this to be evidence for double beta decay without neutrino emission unless the observed counts are due to an unusual phenomenon of unknown origin.

INTRODUCTION

DOUBLE beta decay (hereafter referred to as $\beta\beta$ decay) is a process which can be important as a mode of decay only in the even-A, even-Z isotopes, and then only when an isotope (which does not have the minimum atomic mass in its isobaric series) cannot go to its neighboring odd-Z isobar by simple beta decay or K capture with a lifetime shorter than about 10^{17} years. This situation occurs in the cases of the "stable" isobaric triplets ($A=96$, 124, 130, and 136) and in most of the isobaric doublets (some probable cases are $A=48$, 110, 116, and 150).

The process is the simultaneous emission of two electrons (or positrons) which may or may not be accompanied by two neutrinos. The question of whether or not neutrinos are emitted is an important one since the answer would afford an indirect method of study of that particle, and particularly since it allows an experimental choice between two theories regarding the nature of the neutrino.

The first theory[1] requires that the neutrino (ν) and the antineutrino (ν') are distinctly different particles, one of which is emitted with the electron and the other with the positron. We shall only consider electron emission here, so that the process could be written $n\rightarrow p+e^-+\nu'$, where n is the neutron in the nucleus which changes to the proton p, e^- is the emitted electron and ν' is the antineutrino. Since the emission of an anti-neutrino would be equivalent to the absorption of a neutrino, we might also have the process $\nu+n\rightarrow p+e^-$, but the process $\nu'+n\rightarrow p+e^-$ is forbidden.

In $\beta\beta$ decay involving the emission of two electrons, two neutrons in the nucleus change to two protons. Considering this as a two-step process, the first step would be $n\rightarrow p+e^-+\nu'$ and the second must also be $n\rightarrow p+e^-+\nu'$, since the antineutrino emitted in the first step cannot be absorbed in the second. Thus the overall process becomes $2n\rightarrow 2p+2e^-+2\nu'$. This has two experimental consequences:

(1) The electrons would carry off only part of the available energy of the transition and would therefore have a continuous energy spectrum.

(2) The lifetime of the process would be of the order of 10^{24} years, which is not detectable with currently available experimental equipment.

The second theory[2,3] postulates the existence of only one type of neutrino, which can be either emitted or absorbed in any beta decay process. $\beta\beta$ decay can then take place according to the following scheme: $n\rightarrow p+e^-+\nu$ first, followed by $\nu+n\rightarrow p+e^-$. In this case the neutrino is virtual. For the entire process we may write $2n\rightarrow 2p+2e^-$. We have the following experimental predictions for this reaction:

(1) The two electrons would carry off all of the energy available for the transition (neglecting the recoil energy of the nucleus), so that the total kinetic energy of the electrons would be constant.

(2) The lifetime of the process would be of the order of 10^{17} years for a total available energy of about 5 Mev. (A correction of the order of 10^3 has been made to compensate for the fact that the process is more analogous to allowed beta decay than to superallowed decay.)

In spite of the long lifetime, this latter type of activity should be detectable if we take advantage of the first experimental property. This property was used in an earlier experiment[4] in an attempt to investigate the possible decay of Zr^{96}. The experiment reported herein used the coincidence nature of the activity in combination with the constancy of the energy in an attempt to observe and identify $\beta\beta$ decay in Ca^{48}. Ca^{48} was chosen for its large available energy for the transition (4.3±0.1 Mev plus the rest mass energy of the electrons)[5] and because of the availability of the separated isotope.

THE EXPERIMENT

Although the geometry and over-all method used in this experiment were similar to the earlier experiment,[4]

† Work performed under the auspices of the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
* Now at Bell Telephone Laboratories, Murray Hill, New Jersey.
[1] M. Goeppert-Mayer, Phys. Rev. 48, 512 (1935).
[2] W. H. Furry, Phys. Rev. 56, 1184 (1939).
[3] H. Primakoff, Phys. Rev. 85, 888 (1952).
[4] J. A. McCarthy, Phys. Rev. 90, 853 (1953).
[5] Collins, Nier, and Johnson, Phys. Rev. 86, 408 (1952).

the equipment was considerably different, hence a brief description will be given.

Two scintillation counters (consisting of plastic phosphors mounted on RCA 5819 photomultipliers), each subtending a solid angle, averaged over the source, of 1.8π, were placed on opposite sides of the source. The outputs of these counters were amplified and added electronically. The resultant pulse height was recorded on an Esterline Angus chart recorder whenever a coincidence occurred. Provision was also made for simultaneous recording of all activity without regard to its coincidence or noncoincidence nature.

The equipment was shielded by 1 in. of steel and 3 in. of lead during the early part of the experiment, and during the later part of the experiment was shielded by $\frac{1}{8}$ in. of steel, 3 in. of lead and the mass of the John Hancock Life Insurance Company building, a 571 foot office building. (The later part of the experiment was performed in the sub-basement of the building, 35 feet below ground level.) Further background reduction was accomplished by an arrangement of Geiger tubes in anticoincidence with the scintillation counters.

78 milligrams of Ca in the form of $CaCO_3$ enriched to 84.3 percent Ca^{48} was used.[6] The background measurements were made with a similar sample of Ca containing 97.9 percent Ca^{44} and 0.01 percent Ca^{48}.[7] The samples were mounted between pieces of 1-mil (0.001-in.) aluminum foil. A small amount (about 5 milligrams per square centimeter) of Polyweld, a polystyrene in Xylene organic compound, was used as a binder for the $CaCO_3$. Each sample covered an area of 4.3 cm^2. They were mounted on a wheel so that they could be alternately placed in the counting position without otherwise disturbing the equipment. Such alternation was performed at intervals of approximately 20 hours.

During the portion of the experiment performed in the John Hancock building, the sample identifications were coded by Professor J. W. Rosengren and the key to the code was withheld from the author until the conclusion of the experiment to eliminate possible (but carefully guarded against) "bias effects."

Although the total activity background was too high for the use of total activity data as a significant part of the results of this experiment, such data were taken during part of the experiment and are included as additional evidence against some types of possible contamination.

RESULTS

The results of the portion of the experiment performed in the John Hancock building are presented in Fig. 1 to illustrate the energy spectrum of the background coincidence activity and the method of treatment of the data. The background (Ca^{44}) activity measurements are identified by the dashed line which connects the experimental points. The total number of coincidence events during 230 hours whose total energy lies within an energy interval is plotted at the midpoint of the energy interval. Standard deviations are given for purposes of illustration on two representative points.

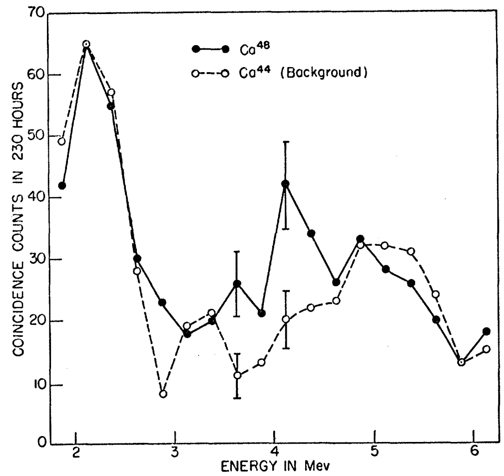

FIG. 1. Coincidence activity observed in the John Hancock Building with Ca^{48} and with Ca^{44} samples. The dashed line identifies the activity with the Ca^{44} sample in position and the solid line identifies the activity with the Ca^{48} sample in counting position.

The low-energy activity is due primarily to natural activity in the surroundings. The broad peak in the neighborhood of 5.5 Mev is primarily due to high-energy particles (probably cosmic in origin) crossing the equipment.

The coincidence activity with the Ca^{48} sample in the counting position is identified by a solid line connecting the experimental points. This activity is, in general, similar to the background activity except in the region near 4 Mev, where the activity is considerably higher than the background. The earlier portions of the experiment showed a similar effect at about 4 Mev but in the earlier runs the background was higher than that shown in Fig. 1 by a factor of 4.

All of the coincidence data were collected and the background, as measured with the Ca^{44} sample, was subtracted from the activity measured with the Ca^{48} sample. Any significant difference, then, is presumably due to activity originating in the Ca^{48}, since the chemical combination, masses and positions of the samples were similar. The difference is presented in Fig. 2, with standard deviations given for each point. This figure represents the difference between the coincidence activity observed in 755 hours with the Ca^{48} sample and that observed in 755 hours with the Ca^{44} sample (in alternating runs, as explained above). The actual number of counts is given. Between 3.75 and 4.5 Mev, for example, there were 595 coincidences in 755 hours with the Ca^{48} sample in counting position and 455 coinci-

[6] This sample was obtained from Professor H. W. Fulbright of the University of Rochester with the consent of the Isotope Division, Oak Ridge National Laboratory, which had performed the isotopic separation and loaned the sample to Professor Fulbright.

[7] This sample was obtained from the Isotope Division, Oak Ridge National Laboratory.

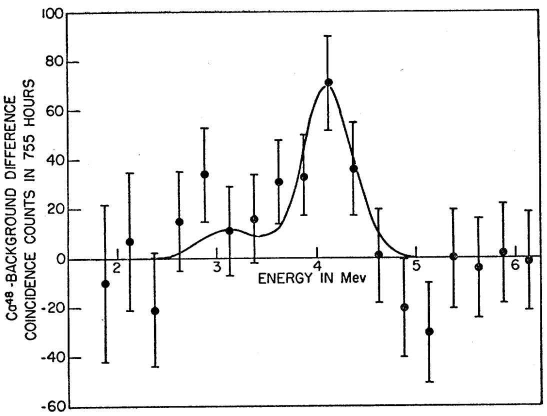

FIG. 2. Difference between coincidence activity with the Ca^{48} sample in position and with the Ca^{44} sample in position in 755 hours of counting with each sample. The curve drawn in indicates the predicted curve if $\beta\beta$ decay occurs with a lifetime of 1.6 $\times 10^{17}$ years.

dences with the Ca^{44} sample in position; the total difference in these three points is therefore 140 counts as shown (33+71+36).

A smooth curve has been drawn in the figure to indicate the predicted energy spectrum if $\beta\beta$ decay occurs in Ca^{48} with a lifetime of 1.6×10^{17} years and an energy release (excluding the rest masses of the electrons) of 4.1 Mev. In calculating this curve, the coincidence efficiency of the equipment was calculated to be $\frac{1}{3}$ (0.4 over-all geometric efficiency assuming isotropy and 0.8 transmission efficiency). In constructing the smaller peak at 3.1 Mev, the assumption was used that the nuclear matrix element in $\beta\beta$ decay of Ca^{48} to the first excited state of Ti^{48} was the same as that to the ground state. This assumption is good only to within a factor of 4 at best in predicting the proper area under the peak (and therefore, of course, the proper height of the peak).

Figure 3 is a similar difference graph for the total

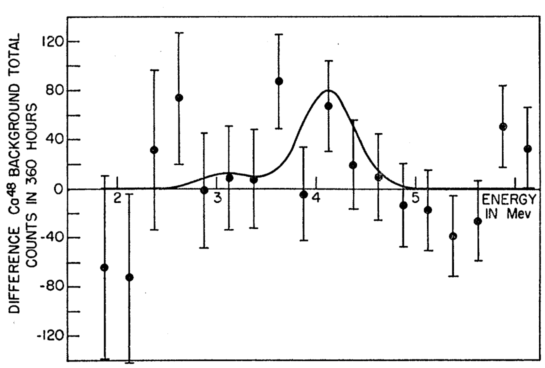

FIG. 3. Difference between total activity with the Ca^{48} sample in position and with the Ca^{44} sample in position in 360 hours of counting with each sample. The curve drawn in indicates the predicted curve if $\beta\beta$ decay occurs with a lifetime of 1.6×10^{17} years.

activities observed with the samples in 360 hours each without regard to their coincidence or noncoincidence nature. This is included not to indicate any evidence for or against $\beta\beta$ decay, but as evidence against some possible types of activity other than $\beta\beta$ decay.

DISCUSSION

The only known type of activity, other than $\beta\beta$ decay, which would result in a coincidence activity with a peaked energy spectrum when investigated with this experimental equipment is internal pair production. This seems a rather unlikely alternative, since it requires an unusual type of activity produced presumably by an unknown and otherwise undetected contaminant, but it must be admitted as a remote possibility. Another possibility is of course experimental error.

If this is $\beta\beta$ decay, the lifetime is $(1.6\pm 0.7)\times 10^{17}$ years. The large uncertainty in the lifetime reflects our lack of knowledge of the exact individual electron energy spectrum and of the angular distribution, although the effect of the latter is largely eliminated by multiple scattering in the source. The efficiency of the coincidence equipment is sensitive to these two factors.

The peak is observed at an energy of 4.1 ± 0.3 Mev, which is in good agreement with the mass spectrographic data[5] (as stated above; these data give 4.3 ± 0.1 Mev as the proper energy for $\beta\beta$ decay of Ca^{48}). The statistical probability of observing the peak shown in Fig. 2 purely by chance in the proper energy region if it is not actually present is less than 1 chance in 10^6.

CONCLUSION

The results presented here, particularly if considered in conjunction with the Zr^{96} evidence,[4] seem to the author to furnish significant evidence that $\beta\beta$ decay can occur without the emission of neutrinos. However, it should be noted here that the experimental results of Inghram and Reynolds[8] do not seem to be compatible with this viewpoint, so that an area of disagreement exists. These latter results[8] do not agree with the theory requiring the emission of neutrinos either, but give a value for the lifetime lying approximately halfway between the predictions of the two theories.

The author would like to take this opportunity to thank Professor Martin Deutsch, whose advice, suggestions, and criticism were invaluable in the performance of this experiment. He is also indebted to Professor H. W. Fulbright of the University of Rochester for his generous cooperation in the loan of the Ca^{48} sample, to the officials of the John Hancock Mutual Life Insurance Company, to Professor J. W. Rosengren, and to the many others who helped and advised him in the course of the experiment.

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[8] M. G. Inghram and J. H. Reynolds, Phys. Rev. **78**, 822 (1950).